AN EMPIRICAL INVESTIGATION ON THE TEMPORAL VARIATIONS OF URBAN HEAT ISLAND IN GREATER KUALA LUMPUR

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE MASTERS OF PHILOSOPHY IN ENVIRONMENTAL SCIENCE (ENVIRONMENTAL MANAGEMENT)

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AN EMPIRICAL INVESTIGATION ON THE TEMPORAL VARIATIONS OF URBAN HEAT ISLAND IN GREATER KUALA LUMPUR

ABSTRACT

Background: Greater Kuala Lumpur (GKL) suffered inevitable territorial urban development with many primary urban areas within the conurbation experiencing the Urban Heat Island (UHI) phenomenon, expressed as the temperature difference between areas of different degrees of urbanization process. Nonetheless, very limited studies have evaluated nor understood the temporal dynamics of canopy-level UHI in the local context. **Aim:** This study investigated the temporal variations of canopy-level UHI in selected urban stations, Petaling Jaya (PJ) and Subang (SUB), of GKL in relation to the reference Sepang (SEP) suburban station. This study also investigated the association between selected meteorological variables (relative humidity and wind speed) and UHI Intensity (UHII) in the urban stations. **Methods:** Hourly dataset of 112 calm and clear days of the year 2016 corresponding to all the monsoon seasons obtained from the meteorological observatories are included in the analysis after excluding the synoptic scale effects. The mean differences between the selected meteorological variables (relative humidity and wind speed) of the urban and suburban stations are tested using one-way ANOVA and Tukey's HSD test. Thereafter, the association between the meteorological variables and UHII is evaluated using Pearson correlation and Multivariate Linear Regression models. **Results:** The difference between the means of the average temperature of PJ-SEP pair is statistically significant during the northeast ($Q = 4.037$, $p < 0.05$) and southwest monsoon ($Q = 11.344$, $p < 0.001$) seasons whereas the SUB-SEP pair registers statistical significance during the southwest monsoon ($Q = 7.742$, $p < 0.001$) only. The yearly average of the UHII in the PJ station (1.25 °C) is higher compared to the SUB station (0.67 °C). High UHII of 0.74 - 1.70 °C is recorded in the PJ station compared to the SUB (0.15 - 1.40 °C) station during relatively drier months associated with the southwest monsoon seasons. In terms of diurnal variations, the daily average of UHII in the PJ station (1.19 °C) is higher compared to the SUB (0.73 °C) station, with the magnitudes surpassing the daily average recorded before sunrise and from late afternoon until the midnight. In addition, the highest cooling rate in SUB (1.10 °C/h) and PJ (0.90 °C/h) is attained around 6 p.m. In contrast, the cooling rate of SEP station is the lowest before sunrise (0.15 – 0.34 °C/h) and after sunset (0.20 – 0.47 °C/h), justifying the development of nocturnal UHI with high intensities in these urban stations. Indeed, most of the hourly UHIIs between 1-3 °C occur at night during all the monsoon seasons. Besides, the relative humidity demonstrated a moderate negative linear relationship with UHII in PJ ($r = -0.568$, $p < 0.001$) and SUB ($r = -0.629$, $p < 0.001$) stations. Likewise, hourly change in UHII (ΔUHII) and relative humidity (ΔRH) also revealed a moderate negative correlation in PJ ($r = -0.508$, $p < 0.001$) and SUB ($r = -0.543$, $p < 0.001$) stations. On the other hand, wind speed exerts a low and moderate negative correlation with UHII in the PJ ($r = -0.450$, $p < 0.001$) and SUB ($r = -0.601$, $p < 0.001$) stations. In terms of hourly changes, a moderate negative relationship ($r = -0.588$, $p < 0.001$) is observed between ΔUHII and wind speed (ΔWS) in the SUB station. Nonetheless, this effect is insignificant ($r = -0.147$, $p = 0.087$) in the PJ station. The combined influences of relative humidity and wind speed on UHII indicating a strong and moderate negative relationship in PJ ($r = -0.714$, $p < 0.001$) and SUB ($r = -0.630$, $p < 0.001$) stations, respectively. **Conclusion:** The findings of this study is expected to fill the existing knowledge gap on the magnitudes of UHII of urban stations in GKL and how strongly the meteorological factors can affect the UHII in an equatorial country like Malaysia by adding more research evidence from the tropical region.

Keywords: Greater Kuala Lumpur, meteorological, monsoon season, temporal variation, tropical, urban heat island

PENYELIDIKAN EMPIRIK MENGENAI VARIASI TEMPORAL FENOMENA PULAU HABA DI GREATER KUALA LUMPUR

ABSTRAK

Latar Belakang: Greater Kuala Lumpur (GKL) mengalami pembangunan yang pesat dengan kebanyakkan bandar utama didalam konurbasi mengalami Fenomena Pulau Haba (FPH), yang merupakan perbezaan suhu diantara kawasan yang berlainan tahap proses urbanisasi. Walaubagaimanapun, kajian yang sangat terhad telah menilai atau memahami dinamika temporal FPH dalam konteks tempatan. **Matlamat:** Kajian ini menyelidik variasi temporal FPH di stesen bandar terpilih seperti Petaling Jaya (PJ) dan Subang (SUB) berbanding dengan stesen pinggir bandar Sepang (SEP) sebagai rujukan. Kajian ini juga mengkaji hubungan antara pemboleh ubah meteorologi terpilih (kelembapan relatif dan kelajuan angin) dan Intensiti FPH (IFPH) di stesen bandar. **Kaedah:** Set data untuk 112 hari yang tenang untuk tahun 2016 yang diperoleh dari stesen meteorologi tempatan telah dianalisis setelah menyingkirkan kesan skala sinoptik. Perbezaan purata diantara pemboleh ubah meteorologi stesen bandar dan pinggir bandar diuji menggunakan ujian ANOVA sehala dan ujian Tukey's HSD. Selepas itu, hubungan diantara pemboleh ubah meteorologi dan IFPH dinilai menggunakan model regresi dan korelasi Pearson. **Hasil:** Perbezaan antara purata suhu untuk pasangan PJ-SEP adalah signifikan pada musim monsun timur laut ($Q = 4.037$, $p < 0.05$) dan monsun barat daya ($Q = 11.344$, $p < 0.001$) sedangkan perbezaan antara purata suhu pasangan SUB-SEP hanya signifikan pada musim monsun barat daya ($Q = 7.742$, $p < 0.001$) sahaja. Purata tahunan IFPH di stesen PJ (1.25 °C) lebih tinggi berbanding dengan stesen SUB (0.67 °C). IFPH yang tinggi (0.74 - 1.70 °C) dicatatkan di stesen PJ berbanding dengan stesen SUB (0.15 - 1.40 °C) pada bulan-bulan yang agak kering yang boleh dikaitkan dengan musim monsun barat daya. Dari segi variasi diurnal, purata IFPH harian di stesen PJ (1.19 °C) lebih tinggi berbanding stesen SUB (0.73 °C), dengan magnitud melebihi purata harian dicatatkan sebelum matahari terbit dan dari petang hingga tengah malam. Tambahan, kadar penyejukan tertinggi di SUB (1.10 °C / jam) dan PJ (0.90 °C / jam) dicapai sekitar jam 6 petang. Sebaliknya, kadar penyejukan stesen SEP adalah yang terendah sebelum matahari terbit (0.15 – 0.34 °C / jam) dan setelah matahari terbenam (0.20 – 0.47 °C / jam), yang menyumbang kepada FPH pada waktu malam dengan intensiti yang lebih tinggi di stesen bandar. Kebanyakan IFPH antara 1-3 ° C berlaku pada waktu malam sepanjang musim tengkujuh. Selain itu, kelembapan relatif menunjukkan hubungan linear negatif sederhana dengan IFPH di stesen PJ ($r = -0.568$, $p < 0.001$) dan SUB ($r = -0.629$, $p < 0.001$). Begitu juga, perubahan IFPH (ΔIFPH) dan kelembapan relatif (ΔKR) setiap jam menunjukkan korelasi negatif sederhana di stesen PJ ($r = -0.508$, $p < 0.001$) dan SUB ($r = -0.543$, $p < 0.001$). Sebaliknya, kelajuan angin memberikan korelasi negatif rendah dan sederhana dengan IFPH di stesen PJ ($r = -0.450$, $p < 0.001$) dan SUB ($r = -0.601$, $p < 0.001$). Hubungan negatif sederhana ($r = -0.588$, $p < 0.001$) diperhatikan diantara ΔIFPH dan kelajuan angin (ΔKA) di stesen SUB. Walaubagaimanapun, kesan ini tidak signifikan ($r = -0.147$, $p = 0.087$) di stesen PJ. Pengaruh gabungan kelembapan relatif dan kelajuan angin pada UHII menunjukkan hubungan negatif yang kuat dan sederhana di stesen PJ ($r = -0.714$, $p < 0.001$) dan SUB ($r = -0.630$, $p < 0.001$). **Kesimpulan:** Penemuan kajian ini diharapkan dapat mengisi jurang pengetahuan yang ada mengenai IFPH di GKL dan seberapa kuat faktor meteorologi dapat mempengaruhi IFPH di negara khatulistiwa seperti Malaysia dengan menambahkan lebih banyak bukti penyelidikan dari kawasan tropika.

Kata kunci: Greater Kuala Lumpur, meteorologi, musim monsun, variasi temporal, tropikal, fenomena pulau haba

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Feel not frustrate saying 'Tis Hard'

Who tries attains striving's reward

Source: Thirukkural (Verse 611) [Translated by Rev Dr. G. U. Pope]

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	Analysis of Variance
APWS	Automated Principal Weather Stations
AT	Atmospheric Temperature
BLUHI	Boundary Layer Urban Heat Island
CFD	Computational Fluid Dynamics
CLUHI	Canopy Layer Urban Heat Island
COP	Conference of the Parties
EBM	Energy Balance Models
ENSO	El-Niño Southern Oscillation
EPA	Environmental Protection Agency
EPDM	Ethylene-Propylene-Diene Monomer (M-Class)
EPU	Economic Planning Unit
ETM	Enhanced Thematic Mapper
ETP	Economic Transformation Programme
GDP	Gross Domestic Product
GIS	Geographical Information System
GKL	Greater Kuala Lumpur
HSD	Honest Significant Difference
HSR	High-Speed Rail System
IPCC	Intergovernmental Panel On Climate Change
KL	Kuala Lumpur
KLCH	Kuala Lumpur City Hall
LST	Land Surface Temperature
LCZ	Local Climate Zones
MetMalaysia	Meteorological Department Of Malaysia
MODIS	Moderate Resolution Imaging Spectroradiometer
MRT	Mass Rapid Transit
NASA	National Aeronautics and Space Administration
NKEA	National Key Economic Areas
NOAA	National Oceanic and Atmospheric Administration
NUP	National Urbanization Policy
PET	Psychologically Equivalent Temperature
RH	Relative Humidity

SEB	Surface Energy Balance
SHIM	Surface Heat Island Model
ST	Surface Temperature
SUHI	Surface Urban Heat Island
T_{MRT}	Mean Radiant Temperature
TM	Terra Modis
TOD	Transit-oriented Developments
t-TEB	Tropical Town Energy Budget Model
UCI	Urban Cool Islands
UCM	Urban Canopy Models
UHI	Urban Heat Island
UHII	Urban Heat Island Intensity
UN	United Nation
WRF	Weather Research and Forecasting
WS	Wind Speed
&	And
°C	Degree Celsius
%	Percentage
α	Alpha
> / ≥	More than / More and equal than
< / ≤	Less than / Less and equal than
△	Delta (Changes)

CHAPTER 1 : INTRODUCTION

Urban Heat Island (UHI) is one of the inimical products of the urbanization process and population expansion in the existing or newly growing cities that serve as a major contributing factor to the global warming (He et al., 2021; Intergovernmental Panel on Climate Change's (IPCC), 2007; Wang and Shu, 2020). The operational definition of UHI describes it as a phenomenon where the cities are relatively warmer than the suburban or rural surroundings due to the anthropogenic modifications to the surface energy balance of the natural environment (Ahmed et al., 2015; Bejaran and Camilloni, 2003; Chew et al., 2021; Półrolniczak et al., 2017). Indeed, proliferating evidence from many extensive studies has reported UHI as a common phenomenon in most of the cities that evolved over a long period of time (Ahmed et al., 2015; Amorim, 2020; Chew et al., 2021; Harun et al., 2020; Santamouris et al., 2015; Sultana and Satyanarayana, 2020). In fact, urbanization process-induced UHI has been propounded as a significant factor of global warming due to observed changes in the decreasing diurnal temperature ranges (the difference between daily maximum and minimum temperatures) and declining warming rates of the lower troposphere compared to the surface (Ramakreshnan et al., 2019; Zhou et al., 2004). In general, the factors attributable to this phenomenon can be classified into two categories such as urban factors (e.g.: city size and morphology, urban materials, urban metabolism and air pollution) and environmental factors (e.g: meteorological conditions and climate zones) (Acero et al., 2013; Chow and Roth, 2006; Feng et al., 2021; Ivajnsic, Kaligaric and Ziberna, 2014; Kim and Baik, 2005; Lai et al., 2021; Oke, 1991; Zhang et al., 2013). Notably, unprecedented population explosions coupled with urban expansions, which are mainly clustered in the tropical urban agglomerations, exert a potential adverse impact on the exacerbation of UHI. In line with this statement, United Nation's (UN) report highlighted that approximately three-quarters of south-east Asian cities that host 53% of the world's current urban population exhibit greater potential for rapid urbanization by 2050, thus intensifying the eventual impacts of UHI in the region (United Nations (UN), 2015). This is a consequential issue for Greater Kuala Lumpur (GKL), which is a fast-growing tropical urban conurbation owing to its crucial role as an engine of economic growth for Malaysia. In fact, notable attention was garnered after the capital city of Kuala Lumpur (KL) was described as getting hotter by 0.6℃ per decade in 2005, which is the world's highest value so far reported for a tropical UHI effect by that time (Davis et al, 2005).

1.1 Background of study

Similar to many south-east Asian megacities, GKL suffered inevitable territorial urban development while hosting one-fifth of the current urban population of Malaysia. Being a dynamic geopolitical region in the heart of south-east Asia, GKL is envisaged to spur the country's economic growth by leveraging upon its strengths on a cosmopolitan population and world-class infrastructure as espoused in Malaysian Tenth Plan (Economic Planning Unit (EPU), 2010). Indeed, its strategic location at the centre of the trade route between China and India, and next to the Straits of Malacca, established GKL to be the nexus of economic and social activities that contributes about 41% of the country's GDP. Due to a notable role as addressed in Malaysian policies, GKL and the other townships within the conurbation observed an overwhelming economic and human capital development that has led to a surge in population density and urban growth footprints as depicted in Figure 1.1.

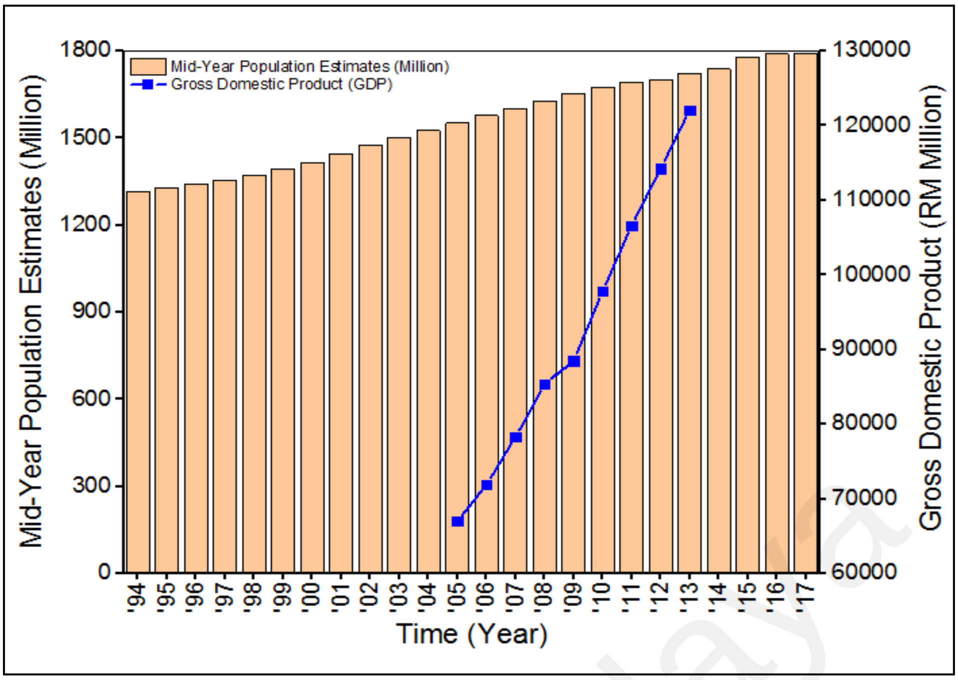

Figure 1.1: The trend of population growth and Gross Domestic Product (GDP) in the national capital of Kuala Lumpur (KL) in the last twenty years (1997-2017)[1].

Being one of the echelons of vibrant commercial centres in Asia and the strategic location at the centre of the trade route between China and India, this region has become a focal point for the commercial activities, investments and infrastructure developments that spur its economic growth (PwC, 2017; Dziauddin, 2019). This has caused a significant growth in the human population in most of the satellite towns within the conurbation due to urban migration, attractive job opportunities as well as increased income and living standards. As a result, high population growth mandates the satellite towns in the conurbation to expand both vertically and horizontally while imposing a greater impact on the local urban climate, often manifested in the form of UHI (Amanollahi et al., 2016; Harun et al., 2020; Ramakreshnan et al., 2019; Shaharuddin et al., 2014; Yusuf et al., 2014). For instance, the findings of Ramakreshnan et al. (2019)

[1]Statistical data on population growth and GDP are obtained from DoS (Department of Statistics) (2017) whereas the graphical illustration is done by Logaraj Ramakreshnan.

revealed that the annual average UHI Intensity (UHII) of two selected urban stations of GKL could reach up to 1.68 °C (Petaling Jaya) and 1.29 °C (Subang) during dry, southwest monsoon seasons. In another study conducted by Harun et al. (2020) in KL, it was discovered that the nighttime UHII could reach up to 6 °C with a significant influence from the wind speed and turbulence.

Despite a limited number of studies, local researchers have still dedicated substantial work to investigating and understanding the nature of Malaysian UHI to predict its characteristics for mitigation purposes. However, tracking the urban heating phenomenon in GKL and the other municipalities within the agglomeration, its temporal and spatial dynamics, contributing factors and the associated consequences over the years is difficult due to the unavailability of continuous measurements or data in this region. While the earliest UHI studies in Malaysia go back to a few decades ago (Sani, 1972; 1986), there is a discernible paucity in UHI assessments after Sani's successive measurements between 1970 and 1990 in KL. A significant number of studies started to emerge only after a study by Elsayed (2012b) reported an increase of 1.5℃ of UHI Intensity (UHII) in KL in 2004 compared to a similar study conducted in 1985 using the same methodology as Sani (Elsayed, 2012b; Sani, 1986). As highlighted in a comprehensive review of local UHI assessments by Ramakreshnan et al. (2018), a very limited number of studies, especially those conducted before 2004, have utilized on-site monitoring approaches to investigate canopy-level UHI phenomenon by deploying stationary or mobile weather stations for real-time data collection (Elsayed, 2012b; Sani, 1972; 1984; 1986; 1987; 1991). However, these studies used datasets of limited temporal resolutions to elucidate the generation and development of UHI in their respective study areas. Nevertheless, there are no studies in GKL that have evaluated the temporal dynamics of canopy-level UHII over annual, seasonal or diurnal scales that usually require big datasets collected over a long-term observational period. Hitherto, the range of timing where the maximum UHII can be reached remains unanswered in the local context. Emerging studies often overlook the importance of obtaining a complete picture of the spatial and temporal development of UHI while developing adaptation and mitigation plans, which is a prerequisite to efficiently targeting the strategies and resources for the evidence-based mitigations.

A wide range of multitude factors can be attributed to the formation of UHI. These factors can be categorized as (i) geography and climate of the urban areas, (ii) three-dimensional characteristics of the urban areas, (iii) urban materials of different thermal characteristics and anthropogenic activities as well as (iv) meteorological conditions of the urban areas (Yang et al., 2020). In the local context, a number of studies are devoted to investigating the contributing factors of UHI. Reduction in vegetation cover (Buyadi, et al., 2013a; 2013b), land-use changes (Salleh et al., 2013; Thani et al, 2013), urban landscape morphology (Thani et al., 2013) and climate change (Salleh et al., 2013) are postulated as the most significant factors of UHI in GKL. While UHI can be associated with both urban and meteorological factors, it is apparent that the aforementioned studies only examined the influence of urban factors on the development and intensification of UHI in GKL. This created a research gap for the upcoming study to explore the influence of meteorological factors on the urban heating phenomenon. Moreover, meteorological variables, which are localized to the specific climate and geographical locations, need to be given similar weightage to elucidate their association with the UHI phenomenon. Hence, more empirical evidence to verify the influence of meteorological factors is required to identify the development of UHI in different urban areas within the conurbation.

1.2 Problem statement

An intensive literature survey reveals some persisting problems in local UHI assessments to be given special attention in this current study. These problems are mainly divided into two categories as follows:

1.2.1 Poor reliability of reported UHI Intensity (UHII) in the selected areas of Greater Kuala Lumpur (GKL)

Firstly, there are no continuous field measurements related to UHI conducted in GKL from 1988 until 2004 before it gains momentum again in 2007. Even though there are a number of studies published starting from 2007 onwards, most of these studies used a very old set of data that was collected years before the publication was done. For example, Hashim, Ahmad and Abdullah (2007), Elsayed (2012b), Salleh et al. (2013), Yusuf et al. (2014), Shaharuddin, Noorazuan, Takeuchi and Noraziah (2014), Morris et al. (2015) and Amanollahi et al. (2016) used data sets that belong to the years 1988, 2004, 1999-2009, 1997-2014, 2008-2009, 2012 and 2000 & 2010 respectively. Hence, the current status and severity of UHII in the urban areas where the aforementioned studies have been conducted are still unknown.

Secondly, contemporary studies delineate a progressive trend toward the application of advanced modelling, simulation (Morris et al., 2017; Morris et al., 2016; Morris et al., 2015) and satellite technology (Amanollahi et al., 2016; Hashim et al., 2007; Salleh et al., 2013; Shaharuddin et al., 2014; Yusuf et al., 2014) in local UHI assessments. However, it should be understood that each of these methodological approaches in the empirical studies are presenting different types of UHIs. For instance, remotely sensed UHI yields surface UHI whereas modelling techniques yield simulated UHI. However, the atmospheric UHI, which is an important measure of the near-surface air temperature that directly correlates to human comfort levels, is often overlooked. Other than this, higher preferences for the space technology and simulation tools compared to in-situ data collection in the current studies lead to an under or overestimation of UHII due to the shortcomings of satellite and simulation technologies with reduced spatial and temporal coverage. Hence, this hinders a proper understanding of how the urbanization process and urban properties influence the accumulation and retention of heat in the city centres over the years. Therefore, assessing the UHI effect using real-time data collected directly from weather stations deployed in the zones of interest in GKL is essential to determine the current, authentic and reliable UHI magnitudes in the city centres.

Thirdly, many local investigators unequivocally used operational definitions of UHI as the urban and rural air temperature comparisons to express UHII in their study areas while leaving no or lesser description about their rural site properties. This is because the term 'rural' can be hardly applied to most of the vernacular GKL landscapes. Most of the areas in GKL underwent rampant development in the last decade due to its function as the main hub for the economic and commercial activities. In this sense, Elsayed (2012b) who discovered the highest UHII of 5.5℃ in KL on Sunday (26 December 2004) used Petaling Jaya as a rural site in her study. Petaling Jaya is a satellite township and a part of the Greater Kuala Lumpur that has progressed rapidly due to the massive rural-urban migration. Upon proper scrutiny, Petaling Jaya is a well-urbanized region that does not represent any rural landscapes that suits the operational definition of UHII used in this study. Considering Petaling Jaya as a rural area is also evocative since a detailed site description or any related site metadata from where the measurements were carried out is not provided in the study. Hence, it can be said that inadequate study site reporting in the form of metadata in local studies often prevents an apprehension of how urban properties influence the UHI phenomenon in the respective study areas. Therefore, the employment of a standard site reporting system such as the Local Climate Zone (LCZ) classification scheme by Stewart and Oke (2012) is needed to describe the surface properties of the study areas for an accurate and authentic UHI assessment.

Fourthly, there are no studies in GKL that have evaluated the temporal dynamics of canopy-level UHI Intensity (UHII) over annual, seasonal or diurnal scales that usually require big datasets collected over a long-term observational period. Hitherto, the range of timing where the maximum UHII can be reached remains unanswered in the local context. Emerging studies often overlook the importance of obtaining a complete picture of the spatial and temporal development of UHI while developing adaptation and mitigation plans, which is a prerequisite to efficiently targeting the strategies and resources for the evidence-based mitigations.

1.2.2 Limited potential factors of UHI are studied in the context of GKL

Even though UHI is considered as the mutual response of both environmental factors and urban factors (Che-Ani et al., 2009; Rizwan, Dennis and Liu, 2008), local studies are still lacking in assessing the influence of environmental (meteorological) factors on UHII. To the current knowledge of the researcher, there are no studies in GKL that have evaluated the association between the environmental factors (particularly, meteorological factors) and UHII while the major attention is mostly given to urban factors such as urban surface properties (Buyadi et al., 2013a; 2013b; Salleh et al., 2013; Thani et al., 2013) and urban materials (Buyadi et al., 2013a). Due to this, the knowledge gap on how strongly the environmental factors can affect the UHII in an equatorial country like Malaysia is still persisting even though studies in countries of other climates such as China (Huang et al., 2020; Lai et al., 2021), United States of America and United

Kingdom (Feng et al., 2021), Korea (Kim and Baik, 2005), Germany (Arnds et al., 2017) and Poland (Klysik and Fortuniak, 1999) recorded some significant relationships between UHII and various meteorological variables.

1.3 Research questions

The following research questions are formulated to guide the development of corresponding research objectives and to test the achievement of those objectives at the end of this study. The research questions of this study are as follows:

i. How do meteorological variables are varying throughout a one-year period of time in the selected urban and suburban stations in GKL?
ii. How the canopy-level UHII varies at both diurnal and seasonal (monsoon) scales in the selected study areas in GKL over a one-year period of time?
iii. What and how strong is the association of selected environmental (meteorological) factors on canopy-level UHII in the selected urban stations in GKL?

1.4 Research objectives

1.4.1 Main Objective

The main objective of the study is to evaluate the canopy-level UHII and its association with the meteorological variables in the selected urban stations in GKL.

1.4.2 Specific objectives:

The specific objectives of the study are as follows:

i. To analyze the temporal variations of meteorological variables in the selected urban and suburban stations in GKL.

ii. To investigate the temporal variations of canopy-level UHII at both diurnal and seasonal scales in the selected urban stations in GKL.

iii. To assess the influence of selected meteorological factors such as relative humidity and wind speed on canopy-level UHII in the selected urban stations in GKL.

1.5 Scope of the study

UHI studies have been conducted and described at different scales such as microscale (1–100 m), local-scale (1–10 km) or mesoscale (10 km) according to the spatial coverage of the measurements (Kim and Brown, 2021). With respect to the number and locations of Automated Principal Weather Stations (APWS) of MetMalaysia in GKL, this study investigates UHI at the local scale, in which the estimated UHII for the selected urban areas is valid for 1–10 km of spatial coverage from where the APWS is located. In terms of seasonal variations, GKL, an equatorial city, is characterized by four main monsoon seasons such as northeast monsoon (November-March), southwest monsoon (June-September) and two shorter inter-monsoon periods (Aflaki et al., 2017; Ramakreshnan et al., 2018). Therefore, the seasonal variations of UHII will be expressed according to these monsoon seasons.

Even though GKL refers to an urban agglomeration that is comprised of ten satellite towns, this study only focuses on three sites, namely Petaling Jaya (PJ), Subang (SUB) and Sepang (SEP). Both PJ and SUB are considered 'urban' stations and SEP will be considered a 'suburban' station in this study due to the differences in the degree of urbanization as identified during the data collection period, which is from 2016 to mid-2017. Furthermore, these locations are also considered due to the availability of fully operating APWS of MetMalaysia. Therefore, this study utilizes meteorological data collected from three APWS of MetMalaysia located in PJ, SUB and SEP to evaluate the temporal variations of UHII at both diurnal and seasonal scales for a one-year (2016) period of time. The year 2016 is of particular interest in this study as it is defined as the warmest year on record since 1880 as per the records by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) (Zhongming et al., 2020). Meantime, a number of areas in GKL also experienced the rarest episodes of hailstorms and other climate externalities in the year 2016 that were associated with the UHI phenomenon (The Star, 2016). Besides, this study assesses the influence of selected meteorological factors such as relative humidity and wind speed on canopy-level UHII in GKL. These variables are chosen due to their notable association with the previous studies in other climate zones (Camilloni and Barrucand, 2012; Huang et al., 2020; Li et al., 2021; Memon and Leung, 2010; Wong et al., 2016) and due to the availability of a complete dataset in all the APWS of MetMalaysia for reliable comparisons.

1.6 Significance of the study

In a bigger scope, this study evaluated the anomalous urban temperature levels that serve as baseline data to determine the severity of urban warming in the selected PJ and SUB stations compared to the less urbanized region in GKL. Such a baseline is crucial to tailor UHI adaptation and mitigation strategies in an effort to achieve Malaysia's pledge made in the Paris Summit 2015 to work towards minimizing a rise in global temperature below 2 ℃ compared to the preindustrial levels. It is worth mentioning that UHI mitigation has been addressed in the Strategic Plan of Petaling Jaya City Council 2021-2025 and Green City Action Plan by Subang Jaya City Council via the implementation of urban greening and riverfront rejuvenation projects (Strategic Planning of Petaling Jaya City Council, 2021; Urbanice Malaysia and MBSJ Voluntary Local Review, 2021).

Nonetheless, neither UHI assessments nor baseline information are available to understand the severity of UHII in these cities and also to track the progress and the successful outcomes of the UHI mitigation strategies. Hence, this study focus on determining the atmospheric temperature-based UHII status in Petaling Jaya and Subang within GKL. As also highlighted in the 26th Conference of Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC), such a baseline is essential to comprehend the contribution of the major cities in GKL to the urban warming as well as to accelerate the country's action towards the goal of limiting the global temperature rise in this century. This is pivotal to achieving the goal of GKL to be among the top 20 most liveable cities with high quality of living standards as visualized in the Economic Transformation Programme (Economic Planning Unit (EPU), 2010).

Apart from this, the results of this study are expected to bridge the existing knowledge and research gap by examining the current UHII in well-built urban areas within the GKL conurbation. This study is essential to understand the temporal dynamics of UHII in a tropical megacity like GKL for a comprehensive apprehension of how urbanization influences the thermal regime of well-developed urban areas within the conurbation. This will be achieved in a holistic manner by examining the temporal variations of the meteorological parameters between the study sites, temporal variations of UHII in the urban areas, diurnal warming rates of the study sites and finally deducing the association between the selected meteorological parameters and UHII in stages. Furthermore, the findings established on the strength of association between the selected meteorological factors and UHII accelerate the understanding of the potential use of synoptic conditions and meteorology characteristic-based UHI mitigation strategies in Malaysia and potentially in other tropical regions. Besides, this study is also expected to fill the existing knowledge gap on how strongly the meteorological factors can affect the

UHII in an equatorial country like Malaysia by adding more research evidence from tropical regions to be compared with studies in other regions. To ensure effective and coherent development of adaptation strategies aimed at improvement of the urban thermal environment, a better understanding of the temporal variability of UHII and the influence of environmental factors thereon is needed.

While the conventional use of 'urban' and 'rural' site classification may be evocative for the GKL landscape, a systematic site classification known as LCZ will be adopted, modified according to the local context and applied to the selected study areas to provide a more objective UHI assessment in the context of GKL. Besides, this study adopted the reference site based on different degrees of development and growth as compared with the urban sites for temperature comparisons. Therefore, this study is expected to provide a better quantification of the UHII interpretation compared to the previous studies.

Besides, canopy-level UHII quantified based on the atmospheric temperature sensed at human height levels is crucial to be associated with the heat-related health impacts in PJ and SUB in future. Most of the studies that are published in the past (Salleh et al., 2013; Yusuf et al., 2014; Amanollahi et al., 2016; Latif and Kamsan, 2017) quantified UHII based on Land Surface Temperatures (LST) collected from satellite imageries. However, recent updates have indicated that air temperature measurements based on ground stations are more reliable and relevant to public health compared to satellite data (Venter et al., 2021). In fact, remotely sensed data is reported to produce a six-fold overestimate of UHII relative to station measurements (Venter et al., 2021). Due to the overestimation, ground measurements that investigate canopy-level UHII are more important as a baseline for future estimates of urban heat risk assessments in PJ and SUB.

1.7 Outline of the thesis

This thesis is organized into five chapters such as introduction (chapter 1), literature review (chapter 2), methodology (chapter 3), results and discussion (chapter 4) as well as a conclusion (chapter 5). The structure enables the readers to locate necessary information in appropriate sections and lowers the risk of missing information. Chapter 1 introduces the background, problem statement, research questions and objectives as well as the significance of the study. Chapter 2 presents the main findings of the literature survey related to the realm of the urban heat island investigations carried out in different regions of GKL in line with the study objectives. At the same time, the methodological limitations, existing research gaps and the recommendations for future studies are highlighted in this chapter to provide a strong ground from where the research questions and the corresponding research objectives are formulated. Chapter 3 outlines the main methodology deployed to examine the temporal variations of selected meteorological parameters and UHII as well as to evaluate the association between them in the selected urban stations in GKL. Chapter 4 illustrates the main findings, discussions and logical synthesis to support the primary outcomes reported in this study. The findings are also compared and contrasted with the findings reported in other regions of similar and different climate settings. Lastly, chapter 5 outlines a comprehensive summary of the main findings of this study to investigate the temporal variations of canopy-level UHII in the selected urban stations of GKL. At the same time, the study implications, limitations and recommendations for the future research work based on the gaps in this study are elaborated in the context of GKL. A list of references, publications and conference presentations is presented afterwards.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Rapid urban development and population growth in the tropical regions demonstrated an inextricable change from the natural environment which has brought about many health and environmental challenges at various scales, mainly in the form of UHI phenomena (Tan, Lim, MatJafri and Abdullah, 2009; Wang and Shu, 2020; Yuan et al., 2020). Indeed, the UN report highlighted that south-east Asian cities are home to 53% of the world's current urban population and are projected to become 64% urban by 2050, intensifying the eventual impacts of UHI in this region (United Nations (UN) 2015). Recently, the urban heating phenomenon received considerable attention from atmospheric scientists of Malaysia as the country was occasionally bombarded with many devastating consequences of rising temperatures such as flash floods (Akasah & Doraisamy, 2014), torrential rain (Gasim, Toriman and Abdullahi, 2014), heat waves (Othman et al., 2016), chronic water shortages (Yew, 2014) and even rare episodes of hail storms (The Star, 2016). This is a consequential issue for GKL, which is a fast-growing tropical urban conurbation owing to its crucial role as an engine of economic growth for Malaysia. However, tracking the urban heating phenomena and the related consequences over the years is difficult due to the unavailability of continuous measurements and studies in this region. From a critical point of view, the inadequacy of field site reporting, poor statements on climate data homogenization, confusing statements of operational definitions of UHII, limited coverage of weather station network, inadequate data collection and delayed publications often decrease the authenticity and question the reliability of previous assessments. Therefore, a comprehensive technique to communicate the site characteristics and to record UHI magnitudes is essential to enhance the assessment accuracy of future UHI studies in Malaysia.

2.2 Generic viewpoints on UHI

2.2.1 Concept of UHI

UHI phenomenon was first investigated and described in the 1810s by Luke Howard, a British scientist who discovered that the city of London is warmer than the undeveloped rural surroundings (Nanjam and Farnood Ahmadi, 2021; Roth and Chow, 2012). Starting from this point, the accumulation of anomalous heating in the vibrant cities started to draw the attention of urban climatologists as one of the most significant influences of human settlements on the earth's climate (Nasir, Ahmad, Zain-Ahmed and Ibrahim, 2015). Contextually, the UHI phenomenon is a typical of urban thermal pollution which occurs due to the development of higher ambient air temperatures in the densely built environment compared to its rural peripheries as depicted in Figure 2.1 (Kang et al., 2022; Rajagopalan, Lim and Jamei, 2014; Roth, 2013; Rovers, 2016; Santamouris, 2015a).

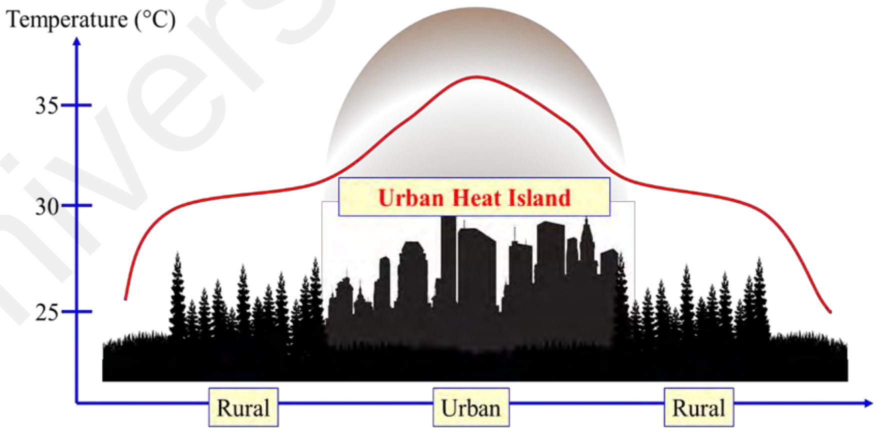

Figure 2.1: The schematic sketch of a typical UHI profile (Source: Aghamohammadi et al., 2021)

UHI phenomenon is induced by the urbanization effects which are closely associated with a larger number of buildings, compact and massive urban structures with narrow street canyons and reduced sky view factor, non-reflective and impermeable surface materials, lack of transpiring vegetation, transport flows, increased energy consumption as well as higher concentrations of urban pollutants (Elsayed, 2012b; Ramakreshnan et al., 2018; Rizwan et al., 2008; Santamouris, 2015a; Wang et al., 2016). The aforementioned urban complexity results in the absorption and retention of heat which are re-emitted after the sunset, creating a steep temperature gradient between urban and rural areas (Benrazavi, Dola, Ujang and Benrazavi, 2016; Gago, Roldan, Pacheco-Torres and Ordóñez, 2013; Ulpiani, 2021; Zhao, Lee, Smith and Oleson, 2014). In addition, the effect of the urban region is not only confined to horizontal temperatures but also to those in the vertical directions with extensive cascading effects as highlighted in a number of studies (Sani, 1991; Solanki et al., 2022).

2.2.2 Types of UHI

Although there are few types of heat islands such as remotely sensed heat islands, subsurface heat islands, daytime heat islands and non-urban heat islands (Stewart, 2011), researchers mainly quantify them as either atmospheric UHI or surface UHI which differ in their development, identification techniques, impacts and mitigation strategies (Environmental protection Agency (EPA), 2009; Benrazavi et al., 2016; Roth, 2013). Notwithstanding these classifications, some new types of heat islands such as industrial heat islands (IHIs) (Mohan et al., 2020) and hydrological UHIs (Zahn et al., 2021) are also documented in the recent literature. IHI refers to the UHI phenomenon that is quantified for the industrial region with reference to natural surfaces such as forests (Meng et al., 2022; Mohan et al., 2020). Being a newly proposed idea, hydrological UHI is defined as the increase in stream temperature due to accelerated urbanization in a particular region (Zahn et al., 2021). However, it should be noted a major portion of UHI studies are expressed either as atmospheric UHI or as Surface UHI (Wang et al., 2022).

Atmospheric UHI occurs due to the accumulation of warmer air in urban areas compared to the cooler air in nearby rural surroundings (Benrazavi et al., 2016). It is often divided into Canopy Layer UHI (CLUHI) and Boundary Layer UHI (BLUHI) (Environmental Protection Agency (EPA), 2009; Peng et al., 2022; Rovers, 2016). CLUHI occurs in the urban layer where people live, particularly below the tops of trees and roofs. On the other hand, BLUHI occurs from the rooftop or treetop level and extends up to the point where urban landscapes no longer influence the atmosphere. CLUHIs are usually investigated based on air temperature collected via ground measurements at human height levels (Ng et al., 2015; Ramakreshnan et al., 2019). In contrast, surface UHI is remotely sensed by using thermal infrared data that allow retrieval of land surface temperatures (Ishak, Hassan, Edros, Zamberi and Rahman, 2011; Li et al., 2022; Mathew et al., 2016). A brief comparison of both types of UHIs, as adapted from (Environmental protection Agency (EPA), 2009) and Roth (2013), is presented in Table 2.1.

Urban Cool Islands (UCIs) or heat sinks are the counterparts of UHIs, which are formed when the rural areas or the reference sites are warmer than the urban areas (Govind and Ramesh, 2019; Ren et al., 2018). The UCIs occur mainly during the afternoon hours when the rural areas receive direct radiation from the sun. The open and sparsely-built land structure in rural areas tends to receive direct and intense solar radiation compared to the urban areas and thus gets warmer compared to the cities. In certain cases, the presence of urban green spaces and the use of light-coloured materials that can reflect the ambient heat in the city centres also contribute to the formation of UCIs (Bartesaghi-Koc et al., 2022; Mendonca, 2009; Zhao et al., 2014). At night, the rural areas tend to release heat at faster rates compared to the cities, which are comprised of heat-trapping urban structures. This creates a steep temperature gradient between urban and rural areas at night that give rise to the development of UHIs in the well-built city centres (Pakarnseree et al., 2018). As observed in other vibrant cities, Shaharuddin, Noorazuan, Takeuchi and Noraziah (2014) witnessed the formation of UCIs at the periphery of GKL with the magnitude much lower during the nighttime as compared to the daytime. They attributed this observation to the process of latent heat release, which is much faster at night in the countryside compared to the urban areas.

Table 2.1: Comparison of Atmospheric UHI and Surface UHI

Characteristics	Atmospheric UHI		Surface UHI
Types	Two		One
	Canopy Layer UHI (CLUHI)	Boundary Layer UHI (BLUHI)	
Definition	The energy balance that influences the air volume inside the canyon through sensible heat transfer from the surface into the canyon.	The extension of urban heat into the UBL through convergence of sensible heat plumes from local scale areas and the entrainment of warmer air from above the UBL	Higher air temperatures during hot and summer days in cities due to intense solar radiation on heat absorbing materials compared to ambient air temperatures in vegetated and shaded rural surroundings.
Temporal developments	Occurs during the nights with very pronounced diurnal variations and the effect during the day time is often negligible.	Occurs during both day and nights with very small magnitude that decreases linearly with the height of UBL.	Occurs during both day and nights with the highest intensity during the day time.
Spatial coverage	Local scale (1– <10 km) (Limited coverage)	Meso-scale (10s km) (High coverage)	Micro-scale (1–100s m) (Limited coverage)
Measuring techniques	Stationary weather stations and mobile transverse methods.	Mainly temperature sensors mounted on airplane, helicopter, balloon and tower.	Remote sensing and often integrated with GIS applications.
Presentation methods	Temperature graphs and isotherm maps	Temperature graphs	Thermal images
Impacts	Energy and water use, thermal comfort, water use, urban air quality and urban ecology.	Local air circulation, air quality, precipitation and thunderstorm activity downwind and plant growing season.	Temperature of storm water runoff, thermal comfort and health of aquatic ecosystems.

2.2.3 Computation of UHI

UHII is a predominant indicator of UHI to evaluate the severity of the urbanization of an area (Rizwan et al., 2008; Sultana and Satyanarayana, 2020). Conventionally, it is determined by comparing the mean and maximum temperatures between urban and rural areas. Meantime, some of the studies also quantified UHII as the temperature discrepancy between areas of different land uses or different degrees of urbanization (Meng et al., 2022; Mohan et al., 2020; Ramakreshnan et al., 2019; Zhou and Chen, 2018). For example, Morris et al. (2015) calculated UHII by subtracting the mean 24 hours canopy layer temperatures of highly vegetated precincts from the mean temperature of the urbanized precincts in Putrajaya. However, there are researchers who also used other approaches in reporting UHII in their studies. In one of such studies, Shaharuddin, Noorazuan, Takeuchi and Noraziah (2014) expressed UHII in Klang Valley by subtracting the minimum value from the maximum value of remotely sensed temperatures which are represented by temperature isotherm lines in their study. In terms of study approaches, a variety of versatile techniques are employed to assess UHII such as in-situ measurements using stationary and mobile weather stations, remotely sensed surface temperature observations as well as simulation and modelling at various scales (Aflaki et al., 2017). Besides those techniques, the Surface Energy Balance (SEB) is another sophisticated approach which is also used to quantify the heat generated and contained in an area (Firozjaei et al., 2020; Mirzaei and Haghighat, 2010; Rizwan et al., 2008).

2.3 UHI status in the tropical cities

According to Arnfield (2003) UHI studies in the equatorial, tropical and sub-tropical settlements are still scanty while a remarkable accumulation of observational heat island studies presents in temperate climates. UHI phenomenon in the tropic, which is generally not well studied, is of importance as the region exhibits higher population growth and socio-economic and environmental significance. In a critical review of UHI studies conducted in the tropics, Giridharan and Emmanuel (2018) underscored that much of the current work is confined largely to East Asia, South Asia and South America despite the large variations in topography, forest cover, land mass and development patterns observed across the tropical belt. The nature of UHI is expected to rely on the geographical variations although their empirical generalizations as discussed by Oke (1982) mostly remain unchanged. For instance, studies in the tropical regions revealed that the smaller sky view factor plays a notable role in the mitigation of heat island effects due to the shading effects of the neighbouring buildings (Wong, 2016). However, contradictory results were obtained in the temperate regions where a larger sky view factor is deemed to reduce the heat island effects (Wong, 2016). UHIs contribute to thermal discomfort and higher energy loads in mid- and low-latitude countries whereas they can function as an asset in reducing heating loads in high-latitude countries with cooler climates (Rajagopalan, 2009). Besides, Zong-Ci, Yong and Jian-Bin (2013) modelled the present heat island effect for eleven regions of the world and identified that the highest warming was concentrated in the Central Asia with an increase of 2.26 ℃ over two decades.

In comparison with the temperate climates, the largest UHIIs are observed in the tropical environment, especially during the driest months (Amorim et al., 2017; Ramakreshnan et al., 2019). The monthly and seasonal variability of synoptic conditions is also associated with a great heterogeneity of UHII in the tropics (Amorim et al., 2017; Chakraborty et al., 2017; Wang et al., 2019). Besides, the heat wave-UHI synergy in a tropical city is also expected to be different from that in the temperate cities. For instance, Chew et al. (2021) found that despite the temperature spike during 2016’s heat waves in Singapore, the UHII maintained its peak near 2.5 ºC during both heat wave and non-heat wave periods. Since temperature plays a vital role in regulating plant development, the phenology of plants is explored as a potential mechanism to detect UHI effects and temperature variations along the urban-rural gradient in the neotropics (Jochner et al., 2013). Despite the growing number of UHI literature in this region, more studies in the rapidly developing tropical and sub-tropical countries, including Malaysia, are both timely and necessary to predict their contribution toward future global warming and climate change.

2.4 UHI status in the tropical context of GKL

2.4.1 GKL as a global city

GKL (3°04’21.11” N, 101°34’08.26” E), regarded conterminous with the more established Klang Valley term, refers to a geographical region that comprises the national capital of KL and its surrounding satellite towns (Economic Planning Unit (EPU), 2010; Shaharuddin et al., 2014; Yusuf et al., 2014). This urban agglomeration is represented by ten city centres such as KL, Petaling Jaya, Shah Alam, Subang Jaya, Klang, Putrajaya, Sepang, Kajang, Ampang and Selayang (Figure 2.2) that function as a vital economic growth cluster contributing eight times the Gross Domestic Product (GDP) of any other region in Malaysia (Economic Planning Unit (EPU), 2010). It covers 2,793 km^2 of land mass in Malaysia (Kwan et al., 2017). Being close to the equator, it experiences a tropical rainforest climate which is characterized by abundant rainfall and sunshine throughout the year (Aflaki et al., 2017). According to the Valuation and Property Service Department’s update in 2009, this region contributed more than 45% of the total amount of constructed houses in the country (Teck-Hong et al., 2012), making it one of the main focuses for urban development and migration.

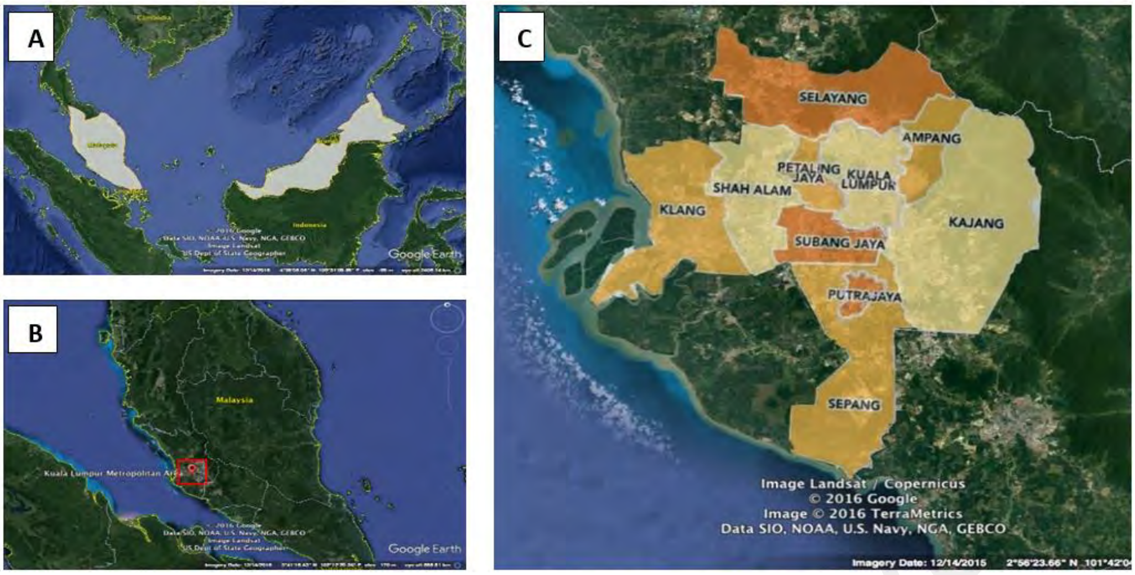

Figure 2.2: (A) Map of Malaysia (B) Location of GKL (C) Detailed map of GKL comprising of ten local authorities (Google Earth, 2016)

GKL becomes one of the main targets of National Key Economic Areas (NKEA) leveraging upon its strengths in a cosmopolitan population and a world-class infrastructure (Economic Planning Unit (EPU), 2010). This scenario aggravates the urban expansion in GKL, which hosts about 21.96% of the current total population (approximately 30 million) of Malaysia. Furthermore, the urban population in GKL is expected to grow even more radically due to its potential for better job opportunities, education, housing, transportation and other economic activities in near future (United Nations (UN), 2015; Elsayed, 2012a). In fact, the urban population of GKL has rocketed from 6 million in 2010 to nearly 7.2 million in 2016 while absorbing a large number of migrants from other states in Malaysia as well as expatriates from various countries (Economic Transformation Programme (ETP), 2014; Yusuf et al., 2014). Being one of the vibrant regions in Peninsular Malaysia, GKL aims to achieve the standard of a world-class metropolis in every aspect, from business infrastructure to liveability that will assume a major regional role for the benefit of all its inhabitants (Kuala Lumpur City Hall (KLCH), 2016). In respect of this, all the local municipalities in GKL have attained a substantial advancement in terms of ongoing construction and infrastructural developments. Despite being an iconic city in Southeast Asia with rapid urban developments, the liveability of GKL still lags behind compared to the other Asian cities. For instance, KL is ranked 85 out of 231 cities surveyed in the Mercer's 21-st annual Quality of Living survey (Mercer, 2019). This scenario accentuates that urban developments in GKL must accommodate a high-quality and harmonious living environment for all the urbanites to elevate the liveability status. Figure 2.3 illustrates land use changes in GKL from 1990 until 2016 where progressive urbanization is eminent with a notable disappearance of green areas over the past decades.

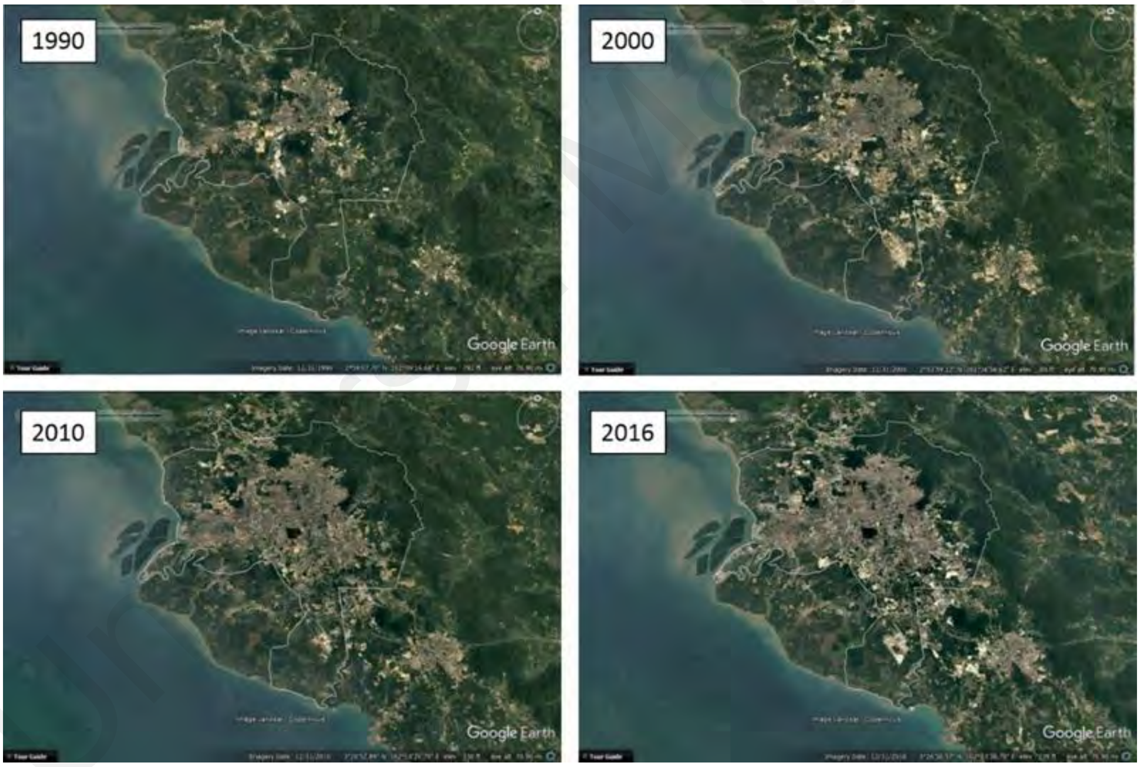

Figure 2.3: Land use changes in GKL from 1990 to 2016 (Google Earth, 2016)

In terms of transportation, the highest incidence of vehicle ownership has made private transportation as the primary mode of travel in GKL (Kuala Lumpur City Hall (KLCH), 2016). High automobile dependency also aggravated the traffic congestion in many high-density urban centres of GKL. In addition, The World Bank (2015) in its 12th

Malaysia Economic Monitor has spotlighted that the time Malaysian urbanites spend in traffic congestion contributed to a loss of 1.1- 2.2% of 2014's GDP. As indicated in the Eleventh Malaysia Plan, KLCH has undertaken various measures to elevate the public transport modal share from 21% to 40% by 2030 to overcome this issue (Economic Planning Unit (EPU) (2016). Currently, a variety of public transport modes including buses, trains and taxis are serving the main city centres and the surrounding regions. Of note, the expansion and enhancement of public transport increased opportunities for transit-oriented developments (TODs) within this region (Yap et al., 2021). Besides, private hire car services such as Grab are increasingly used as convenient transportation modes by the public in the region. Nevertheless, the use of public transport is low compared to the other Asian cities as merely 17% of commuters in KL use public transport compared to 62% in Singapore and 89% in Hong Kong (The World Bank, 2015). In an effort to increase the public transportation usage, the government is currently expanding and constructing an integrated Mass Rapid Transit (MRT) lines that would provide more coverage to areas within the conurbation to cater for the increasing urban population (Economic Transformation Programme (ETP), 2014). Besides, regional connectivity and economic activities will be accelerated by developing a high-speed rail system (HSR) connecting KL and Singapore, which is also envisioned to further enhance business activities between two of these key players of Southeast Asia's largest economic centres (Economic Transformation Programme (ETP), 2014).

The urban development in GKL is mainly in the form of compact and mid- to high-rise residential blocks as present in the largest city centre of KL (Kuala Lumpur City Hall (KLCH), 2016). From a spatial point of view, the city centre of KL consists of five sub-centres such as Sentul-Menjalara, Wangsa Maju-Maluri, Damansara-Penchala, Bukit Jalil-Seputeh and Bandar Tun Razak-Sungai Besi (Kuala Lumpur City Hall (KLCH), 2016). Commercial, industrial and institutional land uses are predominantly found in the city centre whereas most of the residential land use can be found in and around the sub-centres. In terms of residential areas, Ampang, Damansara, Brickfields, Mont Kiara, Sri Hartamas, Bangsar and Kuala Lumpur City Centre are some of the hotspots which are dominated by elevating housing developments projects (Economic Transformation Programme (ETP), 2014). Approximately 66% of commercial and industrial activities are currently centralized within the city centre of KL (Kuala Lumpur City Hall (KLCH), 2016). Currently, the larger manufacturing establishments are tending to relocate outside of the city centre due to the scarcity and high price of land (Kuala Lumpur City Hall (KLCH), 2016). In terms of urban greenery, KL and the Garden City of Putrajaya are collectively working together to increase the amount of greenery within the cities to turn the region into a world-class liveable city. In particular, KL consists of 11 square meters of green space per person and working towards achieving its green goal by planting 100,000 large-canopy trees by 2020 to cater to both social and environmental needs of the urban environment (Economic Transformation Programme (ETP), 2014; Kuala Lumpur City Hall (KLCH), 2016). Meanwhile, cities like Kajang and Sepang still retain a big portion of their natural green areas as located far from the main urban centre of GKL.

2.4.2 A state-of-art review of UHI studies in GKL

2.4.2.1 UHI assessments in GKL

The first foundation for the quantitative assessment of UHI in the tropical region was initiated by Simon Nieuwolt in Singapore in the late 60s and this study is regarded as the first study to be documented for any tropical city (Amanollahi et al., 2016; Roth and Chow, 2012). Then, a comprehensive UHI work was performed in the 1970s in the neighbouring country, Malaysia, by Sani (1972) who is the pioneer UHI researcher in

Malaysia. In the last four decades, Malaysia has witnessed mushrooming research work and activities in understanding UHI, its contributing factors, its eventual impacts on both environment and public health as well as the development of mitigation measures.

(a) ***In-situ monitoring studies***

Sani's in-situ data collection using the temperature traverse technique in and around KL for about two decades revealed that the temperature distributions were normally higher in the built-up city centre compared to the surrounding rural areas (Sani, 1972; 1984, 1986; 1987; 1991). In 1985, Sani mapped the temperature distributions of KL as isotherms in the afternoon and night and discovered that the UHII was greatest during calm and clear sky nights as compared to the days. In the course, Sani also attempted to compare the changing forms and intensity of nocturnal heat islands for four nights with similar weather conditions in 1972, 1975, 1980 and 1985 respectively (Sani, 1986). The comparison results of maximum isotherms of UHI are presented in Table 2.2.

Table 2.2: Comparison of nocturnal UHIs with similar weather conditions in 1972, 1975, 1980 and 1985

Year	Maximum Isotherm (℃)	UHII (℃)
1972	28.5	4.5
1975	28.8	4.4
1980	31.1	6.7
1985	28.0	4.0

There is an irregular pattern in the maximum temperature over the 13-year period although the formations of UHI are significant in these studies. This is attributed to the weakness of spot measurements that failed to cover the temperature distributions over a larger area. In fact, the increase in temperature, which is associated with the land use changes, is not clearly reflected by the isotherms in KL that experienced a rapid urbanization and heavy traffic activities during the study period. By addressing such weaknesses of spot measurements alone, Elsayed (2012b) innovatively combined both the traverse survey method and the weather station networks method to study the formation of heat and cool islands in the city of KL in 2004. Elsayed (2012b) conducted traverse surveys in four major gardens within KL and its peripheries due to the unavailability of weather stations and the need for micro measurements in those areas. An increase of 1.5℃ in UHII for KL city was registered as compared to a similar study done by Sani in 1985 (Sani, 1986). This study also revealed the emergence of more heat islands in the city centre while many cool islands disappeared due to the absorption and retention of heat by thermally bulk urban materials. The study also highlighted a shift of the UHI nucleus from a decaying Chow Kit city to a newly emerging Puduraya city due to continuous human activities, population relocation, traffic congestion, construction and commercial activities during the time the study was conducted. By using four days of temperature and wind data collected from seven sites in KL, Harun et al. (2020) reported 6 ˚C UHII at nighttime and 4˚C of urban cool island intensity at daytime with the effects of land cover on UHI dominating the effects of other factors, including wind speed and turbulence.

(b) ***Remote sensing studies***

Despite the importance of traditional temperature measurements made using both stationary and mobile stations in quantifying UHII, they are still poor in their spatial and temporal resolutions up to certain extents. Hence, a growing number of studies successfully employed wide and versatile applications of satellite technology in determining the surface temperature to quantify UHI effects in built-up areas of GKL. For instance, Yusuf et al. (2014) reported an average gain of 8.4℃ in surface temperature between 1997 and 2013 in GKL using Landsat TM/ETM images. In addition, the satellite technology also helped to assess the contribution of land use patterns in the surface temperature increment over the years. By utilizing both TERRA/MODIS satellite data and Geographical Information System (GIS) contour maps, (Shaharuddin et al., 2014) acquired spatial land surface temperature maps of the GKL region for the years 2008 and 2009 to verify the formation of both UHIs and UCIs according to four monsoon seasons. They found that the average UHII was higher during the day than at night. Moreover, the intermediate monsoon during the daytime of October displayed the highest UHII of 14.5℃. By integrating Landsat images within GIS, (Amanollahi et al., 2016) also found that the highest increase in surface temperatures between the years 2000 (21.5℃) and 2010 (22.7℃) was obtained after more forests were converted into urban areas in Klang Valley. On the other hand, (Salleh et al., 2013) extracted remotely sensed land surface temperatures over a decade (1999-2009) in Putrajaya and deduced that the highest intensity (6.75℃) was in 2006 due to the multiplication of urbanization activities which amplified the surface temperature of the study area. In addition, Shaharuddin et al. (2009) demonstrated the formation of UHIs in the urban areas of Kepong, Jinjang, Segambut, Sentul, Setapak and Bangsar with surface temperatures exceeding 32℃ in accordance with different land use patterns in 1988 (Hashim et al., 2007) retrieved remotely sensed data of both surface temperature and land cover for Selangor in 1988 and discovered that the fast-expanding areas such as Kajang, Cheras and Bandar Baru Bangi have the highest surface temperatures (27.5℃) due to intense thermal energy responses of artificial impervious surface covers such as asphalt and concrete. In order to investigate the relationship between land use and land surface temperature in the city of Shah Alam, Latif and Kamsan (2017) used satellite data to demonstrate that the city was experiencing surface temperature in the range of 26.5 to 33.8 ºC. They propounded that the presence of greeneries is the major influence on the surrounding surface temperature.

(c) ***Modelling and simulation studies***

Despite the limited use in the local studies, SEB is still deemed to be another primary indicator of the urban heating phenomenon that also gives an idea of the heat generated and contained in an area (Rizwan et al., 2008). Hitherto, Tso and Law (1990) successfully performed a simple SEB over selected areas of the city of KL represented by heavy concrete-made building structures. The modelling of building areas and the air mass above the buildings indicated a steep rise of air temperature at 12 pm (34℃) which was followed by a gradual decline to a minimum of 24.9℃ at 5 pm. The results revealed that the maximum peak of temperature at 12 pm was due to heat absorption and storage by the concrete mass during intense solar radiation. Current studies also started to utilize numerical simulations as another viable tool in studying the UHI phenomenon. For instance, Morris et al. (2015) applied a single-layer urban canopy model coupled with the WRF/NOAH LSM modelling system in Putrajaya and discovered that the UHII varied temporally and spatially with a maximum magnitude of 3.1℃ in 2012. In another study, Morris et al. (2016) used the same simulation approach to investigate the local urban climate changes over a decade (1999–2011) in Putrajaya and concluded that the canopy layer temperature of the area was increasing at the rate of 1.66℃ per decade whereas the prevailing UHII of the area was approximately 2.1℃ (Morris et al., 2016). This study also highlights the existence of urban cool islands in 1999, 2007 and 2011. By using the Weather Research and Forecasting (WRF) mesoscale model, Ooi et al. (2017) examined the effect of UHI on the local climate in GKL during a period of weak synoptic forcing. They identified that the daily mean UHII of 0.9 °C with the nocturnal intensities that can reach up to 1.9 °C at night. The results of the above studies are summarized in Table 2.3 according to the ascending order of the years of the assessments.

Table 2.3: A summary of UHIIs recorded in different areas in GKL

Studies in Publication	Year of the Assessment[1]	Study Area	Method	Type[2]	UHII (°C)
Sani (1984)	1972	KL	Temperature Traverse	AT	4.5
Sani (1984)	1975	KL	Temperature Traverse	AT	4.4
Sani (1984)	1980	KL	Temperature Traverse	AT	6.7
Tso and Law (1991)	1983	KL	SEB Modeling	AT	34.0
Sani (1986)	1985	KL	Temperature Traverse	AT	4.0
Shaharuddin et al. (2009)	1988	Kepong, Jinjang, Segambut, Sentul, Setapak & Bangsar	Satellite	ST	> 32.0
Hashim et al. (2007)	1988	Kajang, Cheras & Bandar Baru Bangi	Satellite	ST	> 27.5
Ooi et al. (2017)	2003	GKL	WRF Modeling	AT	1.9
Elsayed (2012c)	2004	KL	Temperature Traverse & Weather Stations	AT	5.5
Salleh et al. (2013)	1999-2009	Putrajaya	Satellite	ST	6.75
Yusuf et al. (2014)	1997-2014	GKL	Satellite	ST	8.4
Amanollahi et al. (2016)	2000&2010	Klang Valley	Satellite	ST	21.5 & 22.7
Shaharuddin et al. (2014)	2008-2009	GKL	Satellite & GIS	ST	14.5
Morris et al. (2015)	2012	Putrajaya	Numerical Simulations	AT	3.1
Latif and Kamsan (2017)	2016	Shah Alam	Satellite	ST	26.5 - 33.8

Harun et al. (2020)	2018	KL	Weather Stations	AT	6.0

[1]It is clear that no studies have been conducted for more than one decade (especially in 1990s) to investigate the urban characteristics on urban microclimate.
[2]AT- Atmospheric temperature; ST- Surface temperature.

From Table 2.3, it can be clearly seen that no UHI measurements have been conducted for more than a decade (after 1988) until Elsayed's study in 2004 (Elsayed, 2012b). In terms of publications, no studies are published in any peer-reviewed scientific journals for more than a decade after Tso and Law's published review in 1991. The publication of UHI studies again gained momentum after Hashim et al.'s published article in 2007. Moreover, serious consideration also needs to be given to the data currency where most of the published papers after 2007 usually utilized a very old set of data that were collected years before the publication was done. This often hinders the researchers to describe the current status and severity of UHII in their respective study areas. Apart from this, not many local studies are published in well-reputed, indexed or peer-reviewed journals. Therefore, the authenticity of the UHI magnitudes reported in those studies is arguable. Besides, current studies seem to show a higher preference for the space technology compared to in-situ data collection to minimize the cost and energy expenditure. Nevertheless, on-spot data collection is equally important for an authentic UHI interpretation to compensate for the shortcomings of the space technology such as reduced spatial and temporal coverage that often leads to an under or over-estimation of UHII.

2.4.2.2 Studies on the contributing factors of UHI in GKL

A growing number of studies showed an inclination towards exploring the major contributing factors and mitigation strategies rather than communicating UHII solely. In one of such studies, Buyadi et al. (2013a) reported that the built-up areas in Shah Alam adjacent to National Botanic Garden recorded an increase of 0.42 °C in surface temperature between 1991 and 2001 when more natural vegetation in the surrounding areas was sacrificed to man-made urban materials such as concrete, stone, metal and asphalt. This study concluded that a considerable reduction in the vegetation density that play important role in heat amelioration through evapotranspiration is deemed to be one of the main contributing factors of UHI. In another study, Buyadi et al. (2013b) estimated about 7.2℃ of increase in urbanization induced-surface temperature increase in the densely built-up areas of Shah Alam city centre over a period of 18 years due to a relative decrease of 17.48% of the vegetation. At a glance, these two studies in the same region highlighted a huge temperature variation related to adjacency to green lungs and rapid land use changes. Salleh et al. (2013) further evaluated the relationship between land use changes and historical climate data to quantify the urbanization impacts on the thermal behaviour of Putrajaya. They found that the surface temperature increased steadily (4.85℃) between 1999 and 2006 due to heavy urbanization activities and eventually decreased (3.20℃) in the successive years. This temperature decrease is associated with a consistent increase of vegetation in the city centre prior to the adoption of the garden-city concept in urban design practices. In the same study, further comparison with global heating data lead to an assumption that remarkably high sea levels in 2006 may have contributed to the peaking temperature record in that year before it declined in the following years. Thani et al. (2013) used a stratified random sampling method to collect both air temperature and relative humidity data from 15 study sites of different landscape morphology, urban geometry, land cover and land use activities in Putrajaya. The results revealed that the highest temperature (39℃) was recorded at the boulevard area with impermeable, paved surfaces, which were intensely warmed by solar radiation and tend to store heat more rapidly than the natural materials. The forested land situated in the northern part of Putrajaya comparatively registered the lowest temperatures (32.5℃) during the study period. The investigation of Harun et al. (2020) in Petaling Jaya indicated that the landscape morphology and its openness towards the sunlight contributed to the peak UHII from 12 - 3 p.m. They recorded that the peak UHII between 6 p.m. and 6 a.m.

ranges most likely within 3 - 5 ˚C in this region. The results from the studies on contributing factors to the formation of UHI are summarized in Table 2.4.

Table 2.4: Factors of UHI and the recorded temperature increments

Studies	Study Area	Factors	Main results
Buyadi et al. (2013a)	Shah Alam	Vegetation loss and man-made urban materials.	Increase of 0.42℃ between 1991 and 2001.
Buyadi et al. (2013b)	Shah Alam	Vegetation loss (17.48% loss)	Increase of 7.2℃ between 1991 and 2009.
Salleh et al. (2013)	Putra Jaya	Land use changes and climate change.	Increase of 4.85℃ between 1999 and 2006.
Thani et al. (2013)	Putra Jaya	Landscape morphology, urban geometry, land cover and land use activities.	Highest temperature of 39℃ at the boulevard area with impermeable, paved surfaces and with adjacent buildings.
Harun et al. (2020)	Petaling Jaya	flat-land and sunny location of PJ	The peak UHII between 6 pm and 6:00 am ranges most likely within 3 - 5 °C

Most of the studies included in this review mainly addressed vegetation depletion and land cover changes as the primary factors of the UHI phenomenon. At the same time, some studies also evaluated the contribution of urban configuration and surface/building materials to the amplification of UHI. However, intense and detailed studies on the thermal bulk properties of urban materials, surface radiative properties, anthropogenic heat production, air pollution and other urban geometric features are still lacking in the context of GKL. As discussed by Aflaki et al. (2016) and Manteghi, Lamit, Remaz, and Aflaki (2016), more advanced techniques such as Computational Fluid Dynamics (CFD) simulations and urban canopy models can be promising options to present the development, distribution, mitigation and the other unexplored contributing factors of UHI in the urban scale.

2.4.2.3 Studies on viable mitigation strategies of UHI in GKL

A growing number of studies started to focus on evaluating the potential remedies for the UHI effect by enhancing the thermal comfort of urbanites to create a conducive urban microclimate. In an attempt to enhance the microclimate and thermal comfort sensation of urban parks, Nasir et al. (2015) simulated three different scenarios of three shades in Shah Alam and identified that the dense and matured trees sustained the microclimate of the park by lowering both air temperature (max. 0.2℃) and mean radiant temperature (max. 15.8℃), thereby increasing the relative humidity and maintaining the wind flow. In another approach of studying the influence of land cover profile on urban cooling (Buyadi, Mohd and Misni, 2014) discussed that the cooling effect increased with the distance from the park boundary. The study deduced that about 3.17℃ of cooling intensity provided by the green areas was only significant within 500 meters distance from the parks. Ahmed et al. (2014) examined the influence of street canyon characteristics and the morphology of blocks in determining the surface temperature distributions in Putrajaya. They found that clustered trees along the street were effective in reducing 9% of the surface temperature compared to scattered and isolated trees. At the same time, 5℃ of surface temperature reductions were recorded in areas where a high-albedo polished white granite material covered the building walls. In addition, it is also found that high surface temperature reductions (3-5℃) and wall temperature reductions (9℃) are recorded in areas where the taller buildings and trees in the boulevard provide shading effects during the intense solar radiation.

In another study, Benrazavi et al. (2016) examined the role of different pavement materials on urban heat reduction in Putrajaya on a clear and sunny day. A significant surface temperature reduction of 15.6% (9.00 a.m. to 12.00 p.m.) and 13.7% (12.00 p.m. to 3.00 p.m.) was recorded by Blue Impala under a shaded location compared to near water or open space. This study also provides a piece of solid evidence that a material's thermal behaviour changes according to location and time. Therefore, a careful selection of materials in specific regions should be done to assist the efforts on urban temperature reduction. Besides, Davis et al. (2005) described an architectural invention of building houses on triangular land within larger hexagonal-shaped land which is known as 'Honeycomb Townships' developed at University Putra Malaysia as thermal comfort housings that require no air conditioning even on the hottest days of the year. As viable mitigation for UHI in Malaysia, this technology was targeted to reduce the electricity consumption spent on air conditioners and potentially save RM 200 billion over the next 30 years. However, the efficiency of this town planning tool in enhancing the thermal comfort in cities is still under research and needs real-time data for validation after the commencement and completion of the project. The above studies are summarized in Table 2.5.

Table 2.5: Proposed UHI mitigations in GKL and reported temperature reductions

Studies	Mitigation Measure	Approach	Temperature Reductions
Nasir et al. (2015)	Increasing vegetation	Simulation	0.2℃ reduction from 10 a.m. till 6.00 p.m.
Buyadi et al. (2014)	Increasing proximity of the parks	Satellite and temperature transect measurements	An average of 3.17℃ reductions within 500 m distance from the park.

Ahmed et al. (2014)	Street canyon characteristics: vegetation, building heights and façade materials.	Stationary temperature measurements	9% of temperature reductions by the clustered trees along the streets. Reduction of 3-5℃ surface temperature and 9℃ of wall temperature due to combined shading effects from trees and tall buildings. Reduction of 5℃ by the use of a high-albedo polished white granite material in buildings.
Benrazavi et al. (2016)	Pavement materials	Surface temperature measurements by infrared thermal imaging camera.	15.6% (9.00 a.m. to 12.00 p.m.) and 13.7% (12.00 p.m. to 3.00 p.m.) of temperature reductions by using Blue Impala (polished finish) under shaded location.
Davis et al. (2005)	Honeycomb Townships, an architectural invention	Theoretical study	Reduce electricity consumption and anthropogenic heat release.

Meanwhile, other approaches are also studied in some other cities of Malaysia. For example, Rajagopalan et al. (2014) investigated the effect of urban geometry and wind flow on UHII in Muar, a developed city in the southern part of Malaysia. Numerical simulations of various urban geometry modifications showed that a step up configuration was the most effective geometry to distribute the wind evenly along the leeward side of the buildings. This improved the overall natural ventilation and thermal comfort at the pedestrian level. Contemporarily, a significant number of researchers also attempted to study the feasibility of adopting green technologies implemented in the temperate countries to the local context. For instance, Sanusi, Shao and Zamri (2014) conducted a preliminary investigation to explore soil temperatures at various depths to identify the role of soil as a heat sink in Selangor. This preliminary study provided baseline data to evaluate the potential of Earth Air Heat Exchanger (EAHE) technology as a cooling means in various building typologies in Malaysia, particularly when the air temperature went beyond 34℃.

In conclusion, the role of vegetation on urban temperature reduction often gains the interest of local researchers although the use of different pavement materials and architectural innovations are occasionally studied as viable remedies. In agreement with Aflaki et al. (2017) and Phelan et al. (2015), future studies need to focus more on the creative and innovative use of greeneries in the form of green roofs, green façades, green corridors and green pavements to reduce the intensification of UHI effects in GKL.

2.5 Methodological conflicts in UHI assessment in GKL

The reliability of the recorded UHII in the existing studies in GKL can only be defensible when clear statements of operational definitions of UHII, a proper system of field site reporting, removal of non-climatic fingerprints from the meteorological data, broader coverage of weather station network and timely and sufficient data are included in the previous assessments. As alluded by Stewart and Oke (2012), many local investigators also unequivocally relied on urban and rural air temperature comparisons to express UHII in their study areas. In the context of GKL, there are a number of studies which still rely on this conventional definition in expressing UHII although the term 'rural' can hardly be applied to the vernacular GKL landscapes. Most of the areas in GKL underwent rampant development in the last decade due to their function as the main hub for the economic and commercial activities (Figure 2.4-2.7). A big portion of the land comprises massive and compact high-rise (Figure 2.4), mid-rise and low-rise building structures (Figure 2.5) which are mostly made up of heat-absorbing façade materials such as glass and concrete (Figure 2.6). In addition, progressive infrastructural developments, commercial and industrial sectors created mass traffic activities (Figure 2.7) that result in high energy use and pollution emissions that amplify the accumulation of urban heat in the cities. In this sense, (Elsayed, 2012b) computed UHII using the same traditional descriptors in KL and discovered that the highest magnitude of 5.5℃ was recorded on Sunday (26 December 2004). However, this temperature comparison was made between the Puduraya sector (urban-28.6℃) and the Petaling Jaya sector (rural-23.1℃). Upon proper scrutiny, Petaling Jaya is a well-urbanized region that does not represent any rural landscapes which suit the operational definition of UHII used in this study. Considering Petaling Jaya as a rural area is also evocative since a detailed site description or any related site metadata from where the measurements were carried out is not provided in the study. Therefore, it is apparent that the selection of the rural station weakens the reliability of the results as it is contaminated with urban effects. In addition, the homogeneity of the collected meteorological data in such a study is also questionable where the absence of a proper site metadata makes it hard to decipher whether non-climatic fingerprints led to the under- or over-estimation of UHII recorded in this study.

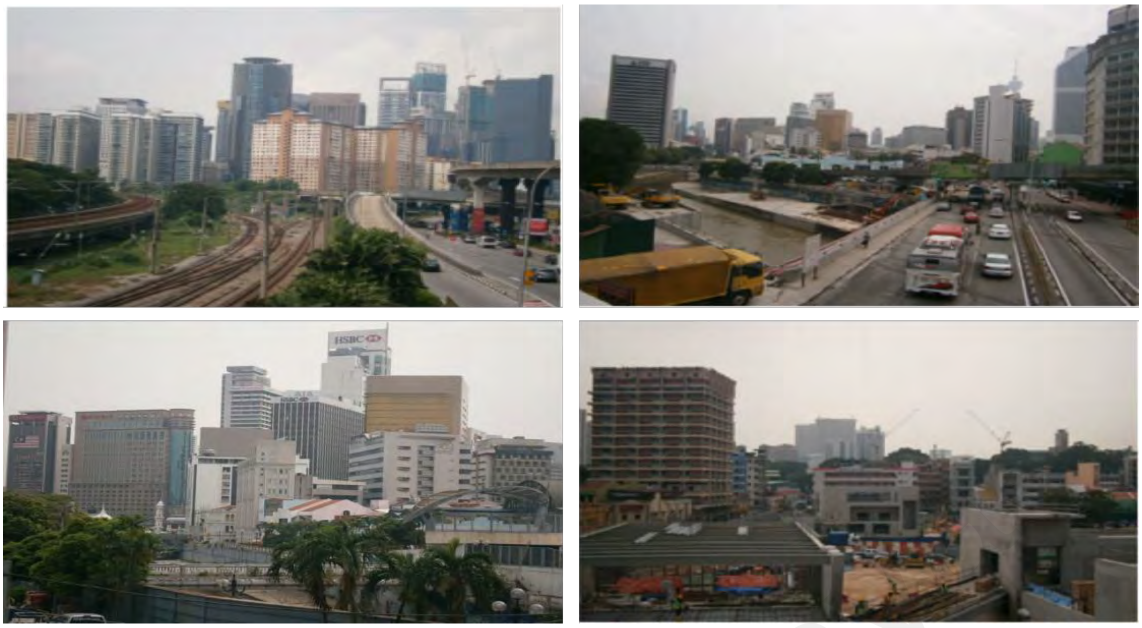

Figure 2.4: Urbanized areas in the city centre of GKL, which comprises of high-rise buildings

Figure 2.5: Commercial areas in the cities of GKL with both low-rise and mid-rise buildings

Figure 2.6: Tall buildings of heat absorbing shiny facades made of glass materials in the cities

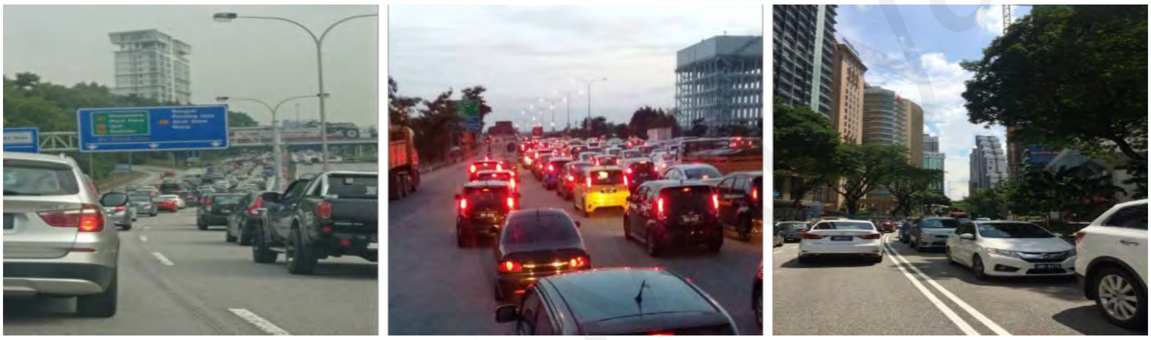

Figure 2.7: Heavy traffic activities during the peak hours that exude heat retaining air pollutants into the atmosphere

Apart from this, limitations in the number of stationary and mobile weather station networks in the study areas also hinder the spatial and temporal coverage of temperature observations. For example, Thani et al. (2013) demonstrated the accumulation of urban heat at various landscape morphologies in Putrajaya based on the manually collected air temperature and relative humidity data from morning until mid-afternoon. The data of these two parameters was only collected for three to five days per week in the selected months. Such a small set of data does not really represent the urban heating phenomenon, which is very significant during the nights. Moreover, a moderate to a bigger dataset with proper control of confounding factors is important to determine the peak intensity of the UHI effect on a diurnal basis. Mirzaei and Haghighat (2010) explained some of the drawbacks of installing measurement devices to include a bigger spatial coverage in terms of cost and time expenditure. However, lacking good weather network coverage often impede the quality of local studies by preventing long-term and large-scale observations. Besides this, the inclusion of a very limited number of parameters such as temperature, wind velocity and relative humidity in UHI assessments prevents the researchers from highlighting the overall three-dimensional spatial distribution of all the parameters' influence on the UHII of an urban area (Morris et al., 2016; Thani et al., 2013). Therefore, future studies should include even broader categories of parameters such as turbulence fluctuations, Mean Radiant Temperature (TMRT) and pollutant concentrations to identify the collective influence of the contributing factors on the intensification of the UHI effect.

Another main problem of the past studies is the use of very outdated data compared to the years the studies were conducted. For instance, Hashim et al. (2007) investigated the formation of UHI in the selected areas in Selangor using a set of land surface temperature data that belong to April 17, 1988. Likewise, Buyadi et al. (2013b) explored the influence of land use on surface temperature distributions in Shah Alam using data derived from Landsat images that belong to the years 1991 and 2001. This practice inhibits the understanding of the current status of UHII despite the growing number of UHI studies in the country. The currency of both in-situ measurements and remotely sensed measurements is essential to address the severity of UHI to stimulate an urgent call for various mitigation approaches. At the same time, adopting satellite technology without proper and solid ground measurements is also deemed to be risky for evaluating UHII. The surface temperature recorded by the sensors only relates to the spatial patterns of upward thermal radiance received by the sensors (Voogt and Oke, 2003). However, the atmospheric UHI differs from the surface UHI in which the turbulence and velocity activities may change the air temperatures inside urban canyons. Therefore, it is crucial to predict the actual atmospheric UHI from the surface by using sensor view models which are not widely adopted in the local studies yet (Grimmond and Oke, 1991).

Besides this, ground-based measurements are fundamental and equally important despite the increasing demand for the remote sensing technologies in UHI quantification recently. Ground measurements are essential in providing a baseline or reference data to evaluate the validity of the results produced by simulation and remote sensing technologies. For instance, Yusuf et al. (2014) claimed that validation of surface temperature extracted from the satellite image in their study in KL was difficult because of insufficient independent meteorological data that covers the study area. Similarly, Hashim et al. (2007) encountered difficulties in performing data quality and accuracy assessment of the study results generated through remote sensing measurements due to a lack of ground temperature information. Hence, more reliable and meaningful results will only be produced when the baseline ground weather station data is available either for comparisons or for thermal infrared data calibration purposes.

2.6 Future prospects and new dimensions in UHI quantification for GKL

The urban-induced warming effects have a higher tendency to create warm bias to the temperature pattern of historical climate series (Stewart and Oke, 2012). A proper justification of the extra heat effects triggered solely by urban transformation activities is essential for the climatologists to exclude such externalities that can contaminate the climate series data. Hence, a standardized guideline to address and report the urban characteristics of the local settings for temperature measurements is vital to distinguish between urban and meteorological influence on temperature increase. However, communicating urban properties using suitable and sufficient parameters is a common weakness among the local studies. Indeed, Stewart (2011) clarified that more than 75% of the observational UHI studies are suffering from poor records of site metadata. Roth (2013) added that many studies claim the rural temperature observations which are taken near urban areas that represent pre-urban conditions. Therefore, the need for a systematic site description is not only beneficial to the climatologists, but also to increase the coherence of UHII reporting.

2.6.1 LCZ as the sophisticated site classification system

The first methodological improvement is required in terms of standardized site classification and detailed communication of site metadata in the local studies. Modern urban climatology investigators such as Ellefsen (1991) and Oke (2004) developed some urban-based climate classification systems to cater for the need for a standardized site characterization. However, these systems are disproportional in their representation of the urban and rural characteristics, thus, not well suited to UHI observations. In fact, it is also difficult to adopt these site classification systems to match with the diverse cultural and economic regions of the contemporary modern cities. To solve such problems, Stewart and Oke developed a site classification system known as ‘Local Climate Zones’ (LCZ) which is also deemed to be a sophisticated approach for site reporting due to its clear communication of physical site properties in terms of their portrayal of built and natural landscapes (Roth, 2013; Stewart and Oke, 2009; Stewart and Oke, 2012).

The LCZs are defined as regions of uniform surface air temperature distribution at horizontal scales of 102 to 104 meters (Stewart and Oke, 2012). Generally, the characterization and categorization of LCZs into 17 zones are based on built types and land cover properties that influence the air temperature at a screen height of one to two meters above the ground as summarized in Table 2.6 (Stewart and Oke, 2012). Being the first framework to evaluate the conceptual division of LCZs with temperature observations and simulation, it expresses UHII as the temperature difference between the local climate zones rather than mere urban and rural temperature discrepancies (Alexander and Mills, 2014; Ng, 2015). Ng (2015) described that this approach is less prone to confusion as the common surface and exposure characteristics of the compared study areas are being explicitly highlighted in her study in Singapore.

Fieldwork needs to be performed to collect appropriate site metadata such as the building geometry, land cover, sky view factor, aspect ratio, mean building or tree height, building surface fraction and impervious surface fraction, terrain roughness class, surface admittance, albedo, anthropogenic heat flux, traffic flow and photographs of the sites to acquire an understanding of the study area in terms of its morphology and influence on the temperature accumulation in urban areas (Ng, 2015; Thomas, Sherin, Ansar and Zachariah, 2014). Indeed, this system is advantageous in providing the flexibility to the researcher to adopt the scheme to suit the local character of the study areas as the internal homogeneity portrayed by each LCZs is unlikely to be found in the real world (Siu and Hart, 2013). In addition, Stewart and Oke (2012) recommended the researchers create new subclasses for the sites that deviate from the standard set of classes shown by combining the built types, land cover types and properties that match their study areas.

Table 2.6: Categories and characteristics of LCZ

Built types		Land cover types		Variable land cover properties	
LCZ 1	Compact high-rise	LCZ A	Dense trees	b	bare trees
LCZ 2	Compact mid-rise	LCZ B	Scattered trees	s	snow cover
LCZ 3	Compact low-rise	LCZ C	Bush, scrub	d	dry ground

LCZ 4	Open high-rise	LCZ D	Low plants	w	wet ground
LCZ 5	Open mid-rise	LCZ E	Bare rock / paved		
LCZ 6	Open low-rise	LCZ F	Bare Soil / sand		
LCZ 7	Lightweight low-rise	LCZ G	Water		
LCZ 8	Large low-rise				
LCZ 9	Sparsely built				
LCZ 10	Heavy industry				

Source: Ng (2015)

2.6.1.1 Adoption of LCZ scheme in the studies in tropical region

A number of researchers have successfully adopted this scheme in their studies in the tropical context. In this regard, Perera, Emmanuel and Mahanama (2012) classified the urban fabric of Colombo, Sri Lanka into appropriate LCZs before simulating the data using the Surface Heat Island Model (SHIM). They associated significant urban warming effects in compact high-rise zones with the zonal properties. On the other hand, Thomas et al. (2014) reported the highest mean UHII in compact mid-rise zones in Kochi, India. Inevitably, they proposed two more zonal properties such as Zone Boundary Distance and the Nearest Adjacent Zone to be added to the original LCZ scheme by Stewart and Oke (2012) after discovering that the UHII of a zone changes according to the nearest zones that it was compared with. The flexibility of the LCZ scheme to allow such modification is beneficial for the researchers to provide a better understanding of the intra-zone variation of UHII of the same classes with different coverage areas and diverse adjacent zones.

2.6.2 The need for synchronous measurements with high spatial and temporal coverage

The second methodological improvement is needed in terms of synchronous measurements and long-term data collection using stationary or mobile weather station networks in the study areas with high spatial and temporal coverage to evaluate both diurnal and seasonal variations of UHI. It should be noted that reporting UHII values using a dataset derived from a very limited weather station's coverage often decreases the reliability of the results in the local studies. At the same time, controlled measurements excluded from non-climatic fingerprints are essential to provide a reasonably good measure of UHII. As discussed earlier, the currency of the data and inclusion of new parameters such as turbulence fluctuations, TMRT, Psychologically Equivalent Temperature (PET), urban metabolism and pollution dispersions are equally important to identify the current status of UHII in the study areas.

2.6.3 The need for advanced modelling and simulation tools in local studies

The third methodological improvement is required in terms of the utilization of advanced modelling and simulation tools to study the development and mitigation of UHIs. Contemporary studies started to focus more on modelling and simulation approaches by replacing an urban area with a prototype that follows the similarity theory between a real case and a small-scale model (Mirzaei and Haghighat, 2010). Despite the challenges of such approaches as reviewed by Wong (2016) and Mirzaei and Haghighat (2010), the Energy Balance Models (EBM), Computational Fluid Dynamics (CFD) simulations and Urban Canopy Models (UCM) are expected to be very effective in understanding the microclimate of the study areas (Mirzaei and Haghighat, 2010; Wong, 2016). With the advancement in the modelling approaches, UCM models are now coupled with other energy simulation models such as the Energy Plus software to assess the impact of urban conditions on the energy consumption of buildings (Wong, 2016). At the same time, researchers like (Karam et al., 2010) developed a new tropical Town Energy Budget model (t-TEB) to cater little urban climate investigations about the tropical Urban Boundary Layers (UBL) which is deemed to be consistent with the timing and dynamics of UHI field observations (Karam et al., 2010). This new t-TEB simulation is also capable to simulate the annual evolution of surface variables within a standard deviation of the observed hourly mean. The application of emerging software such as ENVI-met is also useful in simulating the microclimatic conditions and heat flow in the urban settings (Manteghi et al., 2016). In fact, many recent studies which are conducted in countries with different climates such as Taiwan (Yang, Zhao, Bruse and Meng, 2012), Frankfurt, Germany and Guangzhou, China (Yang et al., 2012), Glasgow, United Kingdom (Emmanuel and Loconsole, 2015), Rome, Italy (Salata, Golasi, de Lieto Vollaro and de Lieto Vollaro, 2015) and Malacca, Malaysia (Manteghi et al., 2016) proved the applicability of ENVI-met in simulating the development of UHI effects. Although being in the infancy stage of using sophisticated modelling and simulation software in the local context, more local studies should start to adopt and use such approaches that can mimic and present real-life phenomena such as UHI.

2.7 Association between meteorological factors and UHI in different climate zones

The factors that contribute to the formation of UHI are often grouped into controllable and uncontrollable variables. Controllable variables include built environmental and anthropogenic factors whereas uncontrollable variables include meteorological and other climate-based parameters (Kotharkar et al., 2019). A number of studies explored the influence of meteorological factors on the urban heating phenomenon. Meteorological variables, which are localized to the specific climate and geographical locations, need to be given similar weightage to elucidate their association with the UHI phenomenon. For instance, Klysik and Fortuniak (1999) reported that UHII higher than 1°C could still be observed when the city's average wind speed is 4 m/s during nighttime and 2 m/s during daytime in Lodz, Poland. Sang, Liu, Liu and Zhang (2000) reported that attenuation of solar radiation is the main reason for reduced UHI in Shenyang, China. Besides, Morris, Simmonds and Plummer (2001) reported that UHII is approximately the fourth root of wind speed and the amount of cloud cover in Melbourne, Australia. Kim and Baik (2002) reported that UHII would decrease with the wind speed greater than 0.8 m/s in Seoul, Korea. The same authors reported that UHII is negatively correlated with wind speed and cloud cover in Seoul, Korea in 2005. Meanwhile, Chow and Roth (2006) identified higher maximum UHII at urban sites which was associated with lower wind speeds in Singapore. Liu, Ji, Zhong, Jiang and Zheng (2007) found that seasonal UHI variation tends to be negatively correlated with the seasonal variation of relative humidity and vapour pressure in Beijing, China. On the other hand, Memon and Leung (2010) demonstrated a strong negative correlation between the UHII and wind speed in Hong Kong. A possible negative correlation between UHII and cloud cover was investigated but could not be substantiated. Camilloni and Barrucand (2012) found a negative trend in the nocturnal UHI intensity that could be explained by an increase in wind speed in Buenos Aires, Argentina. Moreover, Wong, Lai, Low, Chen and Hart (2016) discovered that solar radiation had a negative correlation with UHI in the winter and summer seasons in Hong Kong. Table 2.7 illustrates the findings of the aforementioned studies which have evaluated the influence of selected meteorological factors on the UHI effect using real-time data in different climate zones.

Table 2.7: Studies that evaluated the association between selected meteorological factors and UHI

Study	Location	Climate	Method[1]	Atmospheric Layer[2]	Meteorological factors	Correlation
Klysik and Fortuniak, (1999)	Lodz, Poland	Continental	WS	UCL	Wind speed	-
Sang et al. (2000)	Shenyang, China	Continental	WS, Numerical model	UBL	Solar radiation	- (attenuation by smoke)
Morris et al. (2001)	Melbourne, Australia	Temperate	WS, Regression	UCL	Wind speed Cloud cover	- -
Kim and Baik (2002)	Seoul, Korea	Continental	WS, Regression	UCL	Wind speed	-
Kim and Baik (2005)	Seoul, Korea	Continental	WS, EOF analysis	UCL	Wind speed Cloud cover	- -
Chow and Roth (2006)	Singapore	Tropical	WS	UCL	Wind speed	-
Liu et al. (2007)	Beijing, China	Continental	WS	UCL	Relative humidity Vapour pressure	- -
Memon and Leung (2010)	Hong Kong	Temperate	WS, Regression	UCL	Wind speed Solar radiation Cloud cover	- - +

Camilloni and Barrucand (2012)	Buenos Aires, Argentina	Temperate	WS	UCL	Cloud cover	-
					Wind speed	-
Wong et al. (2016)	Hong Kong	Temperate	WS	UCL	Solar radiation	-
					Temperature	-
					Relative humidity	-

[1]WS = Weather Stations
[2]UCL = Urban Canopy Layer, UBL = Urban Boundary Layer

At a glance, while wind speed and cloud cover become the most investigated meteorological variables, a plethora of studies are concentrated in temperate and continental climate zones. Although the influence of meteorological factors on UHI is salient, studies in tropical climates are still scanty and more scholarly studies within hot and humid climates are required to enrich the persisting knowledge gap. Hence, GKL could be an ideal tropical destination to examine the meteorological factors' influence on UHI effects in a local context.

2.8 Operational definitions of the meteorological parameters and study variables of this study

The operational definitions of the important technical terms, data and measurements that are used in the data collection, analysis and reporting of the findings are presented in this section. This is to facilitate the standardization of data and methods used in this study to minimize the risk of producing inconsistent findings upon replication of this study in other contexts (Leslie-Mazwi et al., 2018). As the field grows, the use of consistently defined nomenclature is pivotal to facilitating quality improvement in UHI studies (Leslie-Mazwi et al., 2018).

2.8.1 Air temperature

Air temperature is a physical quantity that refers to the degree of heat that is present in the ambient air of the urban and suburban stations (Landsberg et al., 2011). It represents the thermal energy present in the ambient air in the study sites that serve as the main parameter for the quantification of urban heat island intensity (UHII) of the selected urban stations. In this study, air temperature or called screen-height temperature is recorded at a standard height of 1.5 m above the ground in all the study sites and is included in the calculation of UHII (Jarraud, 2008; Stewart and Oke, 2012).

2.8.2 Relative humidity

In general, humidity refers to the concentration of water vapour in the air. Relative humidity, on the other hand, describes the present state of absolute humidity (water content in the ambient air) relative to a maximum humidity given the same temperature (Yang, Ren and Hou, 2017).

2.8.3 Wind speed

Wind speed is an expression for the atmospheric quantity caused by air moving from high to low pressure and influenced by the changes in the temperatures (Perim et al., 2017). In this study, days with wind speeds (<5.00 m/s) according to the Beaufort's scale are included in the analysis (Met Office, 2016).

2.8.4 Urban Heat Island Intensity (UHII)

The conventional definition of UHII refers to the temperature contrast between the urban and rural areas (Ahmed et al., 2015; Półrolniczak et al., 2017). As the use of the term 'rural' is debatable and hardly fits the vernacular GKL, this study defined UHII as the temperature difference between the urban and suburban stations in regard to the different degrees of urbanization between the urban and reference suburban stations (Ezber, Lutfi Sen, Kindap, and Karaca, 2007; Memon, Leung, Liu, and Leung, 2011). Of note, UHII serves as a quantifiable indicator for the thermal modification caused by the urbanization process in the cities relative to the surrounding rural or suburban peripheries.

2.8.5 Cooling (warming) rate of the urban and suburban stations

The cooling or warming rate is an urban climate metric that presents the rate of the surface warming or cooling over a specific time (changes in temperature over changes in time) at the urban and suburban stations (Makokha and Shisanya, 2010). In this study, the cooling (warming) rate is expressed on a diurnal scale that examines the average temperature changes between the hours in a day. Associated with UHII, the comparison of cooling (warming) rates between different land uses is a direct indicator of the heat accumulated in the city over time with respect to local-scale urban climate. Moreover, a comparison of the cooling (warming) between urban and suburban stations under ideal local and synoptic weather conditions enables the comprehension of UHI in terms of radiative cooling differences caused by land use and morphology of those stations (Makokha and Shisanya, 2010).

2.8.6 Seasonal and diurnal scales

Seasonal variation refers to a specific type of pattern exhibited by the meteorological parameters and UHII in a time series (months) within a year, often observed in a regular and repeated pattern. In the context of the present study, seasonal variation is expressed in terms of monsoon seasons such as the wettest northeast monsoon (November-March), the driest southwest monsoon (June-September) as well as two relatively shorter inter-monsoon periods, namely pre-northeast monsoon (September-October) and pre-southwest monsoon (April-May) (Aflaki et al., 2017). On the other hand, diurnal variation refers to the patterns of the meteorological parameters and UHII within a day, displayed in 24 hours.

2.9 Summary

The critical review of the aforementioned UHI studies in the context of GKL presents an analysis of UHI assessments, the methodological shortcomings and the recommendations to enhance those problems in future studies. Even though GKL represents a large conurbation comprised of ten major cities, UHI studies are mainly concentrated in KL with a very small number of studies carried out in other cities such as Putrajaya, Kajang and Shah Alam. It is worth noting that there are no UHI assessments conducted in Selayang, Ampang, Petaling Jaya, Subang Jaya and Sepang until 2016 (the present study covers Petaling Jaya and Subang). Hence, there is no record of UHII that corresponds to any heat-related environmental or health implications in these cities. In addition to this, the investigation of the temporal dynamics of UHII is also limited to the context of GKL. While the available UHI studies are still scanty, the last decade has witnessed a mushrooming number of studies assessing the factors and mitigation of UHI in this region. Nonetheless, the conventional use of urban-rural temperature discrepancies in UHI quantifications where the measurements in the rural sites were done near urban areas, improper field site reporting, failure to address non-climatic fingerprints from the meteorological data, limited coverage of weather station network and the currency of data are the main weaknesses found in the local studies. Therefore, the replacement of urban-rural descriptors with more reliable site characterization such as the LCZ classification system is expected to increase the authenticity and coherence of measurements. Proper site reporting, controlled and synchronous measurements, expansion of weather station networks and inclusion of more vital parameters in the UHI studies will enhance the understanding of the status and severity of this phenomenon.

Advancements and progress in modelling and simulation applications such as SEB, CFD and UCM are compromising methods to overcome the limitations of the observational methods in future studies. However, the feasibility of integrating these applications into ground measurements to examine the canopy-level UHI still needs an in-depth investigation, especially in the tropical region. In addition, researchers can also explore different modelling and simulation approaches by integrating various climate models, urban models and building models to provide a better understanding of the mechanism of UHI driven by urbanization.

On the other hand, the influence of urban factors such as urban materials and surface characteristics on UHI are studied in a number of studies. However, being a tropical country characterized by distinct synoptic meteorological conditions, very limited studies attempted to deduce the association between meteorological variables and UHII. Future studies can make use of this gap to work on identifying the potential relationship between the meteorological variables and UHII in a tropical country like GLK. Despite its significant influence on urban microclimate and thermal comfort of urbanites, the UHI phenomenon is inadequately addressed and communicated in any local policies or guidelines. Hence, a collective effort from local authorities to incorporate and mandate the appropriate laws, regulations and best practices for developers to eliminate the UHI effects via more climate-friendly design approaches is essentially needed in future city developments. Overall, the aspiration of creating world-class sustainable cities is only achievable when related legislative policies are mainstreamed into planning and the development control system of cities in Malaysia. Thus, the commitment and active participation of every stakeholder in tackling UHI impacts is a fundamental prerequisite for GKL to achieve a sustainable and world-class liveable city status. They are also necessary as proof of Malaysia's pledge made in the Paris Summit 2015 and COP26 to work towards minimizing a rise in global temperature below 2℃ compared to the preindustrial levels (Morgan, Dagnet and Tirpak, 2014; Sanderson, 2021).

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CHAPTER 3 : METHODOLOGY

3.1 Introduction

This chapter outlines the main methodology deployed to examine the temporal variations of selected meteorological parameters and UHII as well as to evaluate the association between them in the selected urban stations in GKL. Hence, the following sections will explicitly describe the study design, research framework, study sites, datasets and methods associated with the data acquisition and data analyses in this study.

3.2 Study design

This study employs a retrospective, quantitative empirical research design that aims to investigate the temporal variations of UHII at both seasonal and diurnal scales in the selected urban stations (PJ and SUB) by setting a suburban station (SEP) as a reference station for temperature comparisons for the year 2016. The meteorological parameters such as air temperature, relative humidity, wind speed and rainfall for the year 2016 that are measured at human height level (2 m above the ground) in the study areas are collected from the meteorological observatories of the Malaysian Meteorological Department (MetMalaysia). Models such as ANOVA, Tukey-test, Multiple Linear Regression and Pearson correlation are utilized to test the mean difference between the selected meteorological parameters and also to examine the association and its strength between the meteorological parameters and UHII in the selected urban stations in GKL. A detailed description of the methods is presented in the following sections.

3.3 Research flowchart

The flowchart of the study is illustrated in Figure 3.1.

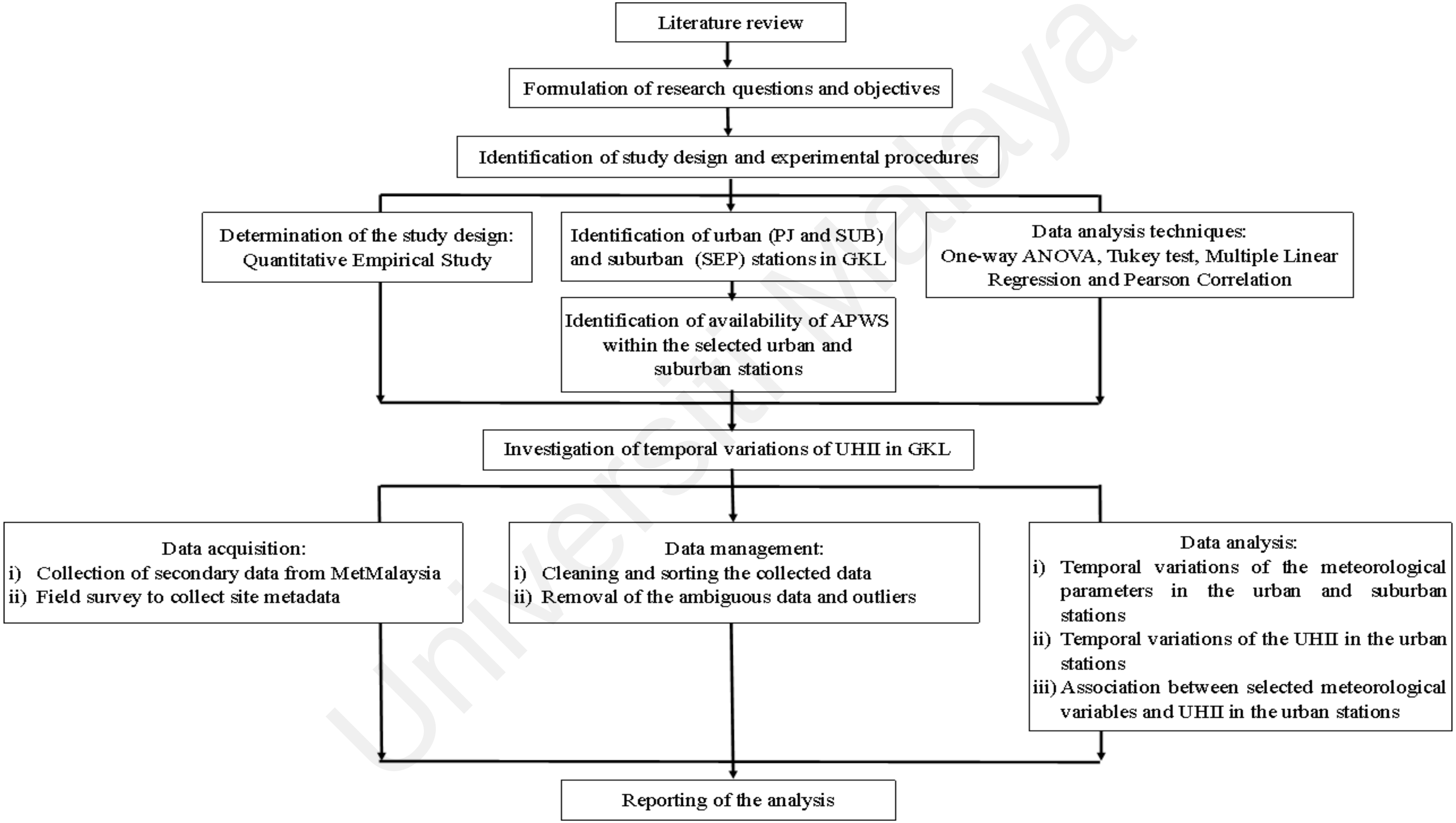


Figure 3.1: Research flow chart

3.4 Sampling technique

This retrospective study utilized secondary meteorological datasets obtained from the meteorological observatories of the Malaysian Meteorological Department (MetMalaysia), which is responsible for monitoring the onshore, sea and air weather conditions continuously throughout the country. In particular, the selection of study sites, meteorological observatories and meteorological data are achieved based on several criteria in accordance with the fulfilment of the study objectives. In addition, the following criteria have adhered to during the selection of the study sites:

i. The selected urban (PJ and SUB) stations display different degrees of urbanization compared to the reference, suburban (SEP) station for temperature comparisons. The varying degree of urbanization exerts significant climatic variations in each respective station due to the long-term influence of urbanization and varying topography (artificial physical features in an area).

ii. All the selected urban and suburban stations must be accommodated by a simultaneously operating integrated Automated Principal Weather Stations (APWS) of MetMalaysia, which are designed in compliance with the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO) standards to fulfil international requirements for weather and climate monitoring. The WMO standards are adhered to in terms of the location of meteorological stations, instrumentation, observing programme as well as data collection, processing and reporting methods (Wang and Shu, 2020).

iii. All the APWS must collect the fundamental weather data such as ambient temperature, relative humidity, wind speed, atmospheric pressure and rainfall.

3.5 General description of study area

3.5.1 Greater Kuala Lumpur (GKL)

GKL (3º 09'N; 101º 44'E), also known as Klang Valley, is a megalopolis that comprises the Federal Territory of KL and its surrounding municipalities as illustrated in Figure 3.2. It covers an 8,236 km^2 area in the southern part of Malaysia (Morris et al., 2017). It experiences a tropical rainforest climate (Köppen-Geiger: *Af*) with annual hot and humid climatic conditions and heavy tropical rains due to its proximity to the Earth's equator (Aflaki et al., 2016; Peel, Finlayson, and McMahon, 2007). Located 21 m above the mean sea level, it is characterized by near-uniform monthly mean temperature (26.8-27 ˚C) and high mean relative humidity (63-68%) (Morris et al., 2017).

In parallel to the aspiration of GKL to be one of the top 20 world-class liveable cities that generate substantial remuneration for the national income (Chuen, Karim, and Yusoff, 2014), a higher rate of urbanization is predicted in near future, catalysed by infrastructure developments, urban migrations and better career prospects. GKL experiences two main seasons including the wet, northeast monsoon (November to March) and the dry, southwest monsoon (June to September) with two relatively shorter inter-monsoon periods between the above-mentioned monsoons (Aflaki et al., 2017; Satari, Zubairi, Hussin and Hassan, 2015). However, GKL is presumed to be less affected by the exact intensity of both monsoon winds due to its strategic geographical location in the middle of Sumatra island (southwest) and Titiwangsa (northeast) mountain range that provides shielding effect from the prevailing monsoon winds (Ooi, Chan, Subramaniam, Morris and Oozeer, 2017). These unique geographical criteria make the temporal, particularly seasonal canopy-level UHI assessment in GKL, more interesting and vital to be compared with the characteristics of other tropical UHIs.

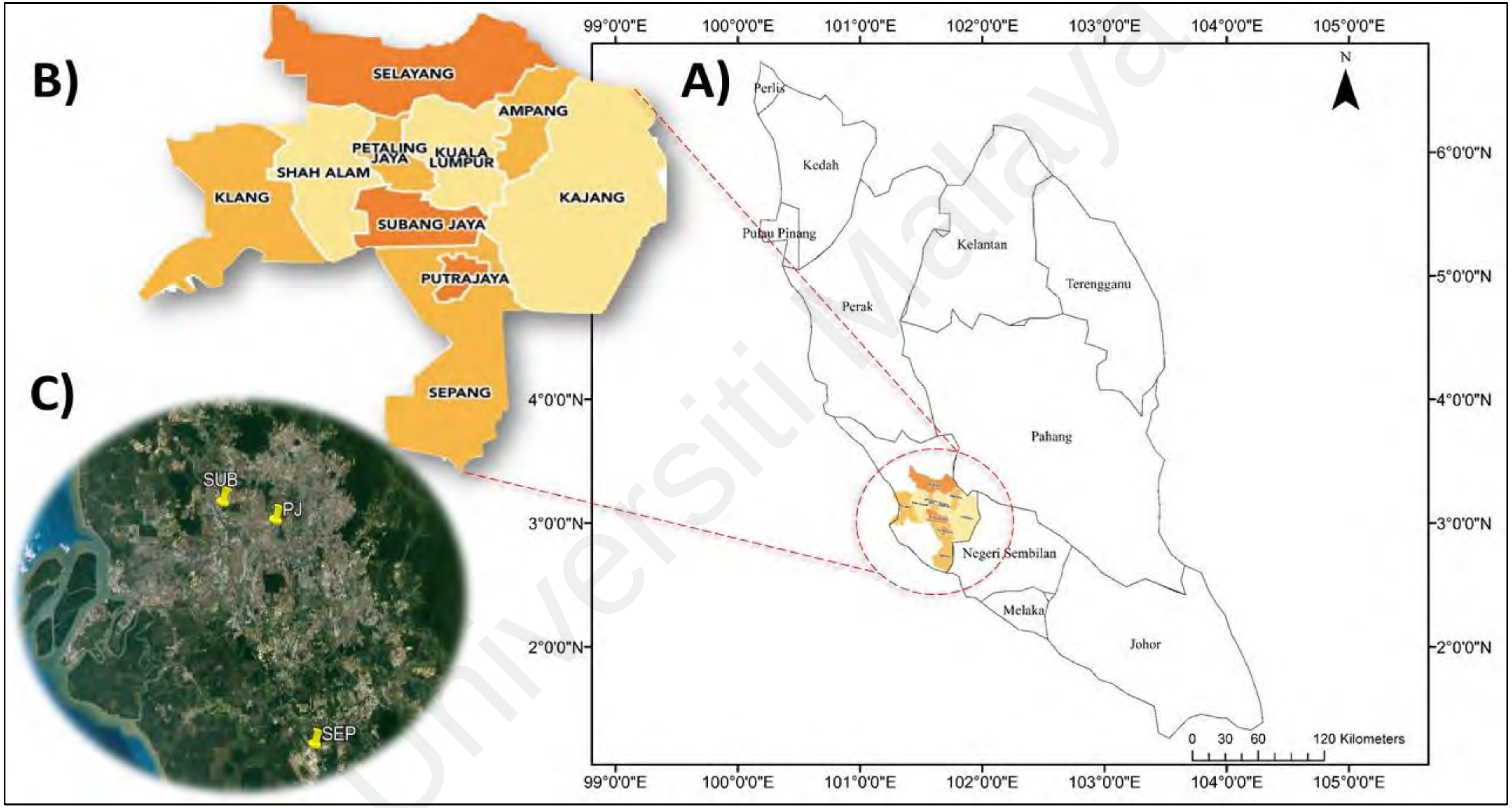


Figure 3.2: Geographical location of GKL. (A) Map of Peninsular Malaysia indicating the exact location of GKL, (B) GKL conurbation comprises of ten townships, (C) Aerial view of GKL showing two urban stations (Petaling Jaya, PJ & Subang, SUB) and one suburban (reference) station (Sepang-SEP) situated at regions of different degrees of urbanization.

3.6 Description of the urban and suburban stations in GKL

This section provides a general description of the urban and suburban stations included in this study. Meantime, the descriptions of the meteorological observatories (weather stations) and the general land use within 5 km of their surrounding are presented in detail in section 3.7.

3.6.1 Petaling Jaya (PJ) station

Petaling Jaya (3°04′ N, 101°39′ E), which will be addressed as 'PJ station' in this study (Figure 3.2), refers to a satellite township in the state of Selangor. It is one of the central industrial and commercial townships of GKL (Shabanda et al., 2021). Due to its proximity to KL, the capital city of Malaysia, there is an increasing trend in terms of the commercial, traffic and industrial activities that accelerate rapid urbanization, traffic density and population explosion (Jamhari et al., 2014). This has caused a myriad of environmental issues such as severe episodes of air pollution (Jamhari et al., 2014), traffic congestion (Shabanda et al., 2021) and urban health challenges (Ling et al., 2014). In terms of climate, the PJ station is characterized by a tropical rainforest climate with an average annual temperature of about 30 °C and average relative humidity of 75%, with an average annual rainfall of about 3300 mm (Shabanda et al., 2021). In addition, the months of June and July are considered the driest months as occasionally experience drought conditions and water rationing in the neighbourhood during this period.

3.6.2 Subang (SUB) station

Subang (3°7′ N, 101°33′ E), which will be called as 'SUB station' in this study (Figure 3.2), is another township located 16.3 m above sea level in the heart of GKL. Similar to PJ station, SUB station's location near Kuala Lumpur has made the city emerge as another hub for commercial, residential, industrial and traffic activities (Saimi et al., 2020). Experiencing a tropical climate, the variations of the meteorological parameters are relatively uniform throughout a typical year (Rahman and Dewsbury, 2007). The daily temperatures are usually recorded within the range of 23 - 34 °C. The annual rainfall is about 2360 mm. The wettest and driest months are April and June due to the differences in the rainfalls received by the city (Saimi et al., 2020). Due to significant variations between the temperature and rainfall received by the city, it records a high number of vector-borne diseases (Adilah-Amrannudin et al., 2016).

3.6.3 Sepang (SEP) station

Sepang (2°8′ N, 101°73′ E), hereafter will be addressed as 'SEP station' (Figure 3.2), is delineated to the southern part of GKL. Unlike PJ and SUB stations, SEP station exhibits a lower degree of development and is therefore selected as a reference suburban station in this study. The minimum and maximum temperatures range from 22.8 - 34.8 °C (Muhamad et al., 2010). The existing developments are mostly based on agricultural activities. With the development of Kuala Lumpur International Airport (KLIA) and the Federal Territory of Putrajaya, it manifests a distinct land use with patches of rural and semi-urban areas interspersed between the dense vegetation cover (Mahadi et al., 2017).

3.7 Description of observation sites and meteorological observatories of MetMalaysia

The conventional approach in site selection for UHI studies is that one or more urban stations will be chosen and their average air/surface temperature will be compared with the air/surface temperature of a reference rural station (Stewart and Oke, 2012). However, a number of researchers argued that this concept is not restricted to urban-rural temperature discrepancy only, but rather covered a wide range of diversified ideas such as temperature comparison between areas of different degrees of development, growth or maturation (Ezber, Lutfi Sen, Kindap and Karaca, 2007; Memon, Leung, Liu and Leung, 2011). In addition, the selection of a rural station can be difficult in certain regions that underwent rapid urbanization. As a matter of fact, the existing smaller pockets of rural areas in such regions can be contaminated with pre-urban conditions that do not provide a better representation of rural climatological attributes.

This is also the case of GKL whereby the term rural does not fit most of the vernacular GKL landscapes. By considering this, this study selected SEP, a suburban station, which is located approximately 45 km far from the densely-urbanized cluster of GKL as shown in Figure 3.2 (C), as a reference station to be compared with the other two urban stations, such as PJ and SUB stations. Furthermore, the SEP station is sparsely-built and still retains a significant proportion of vegetation cover and permeable surface cover, which is a relatively different landform compared to the other urban stations. At the same time, the meteorological observatories at the urban stations, PJ and SUB, are delineated to the northern site of GKL whereby the suburban SEP station is located in the southern part of GKL. Such geographical locations of the meteorological observatories provide a good spatial representation of the background meteorological conditions.

As suggested by Oke (2004), it should be noted that these meteorological observatories are free from any form of artificial heat-generating sources such as emissions from vehicles, air conditioners and anthropogenic activities. In addition, these observatories should encompass proper ventilation to ensure the acquisition of representative meteorological observations of the urban and suburban stations. Figure 3.3 demonstrates the aerial view and landscape view photographs of the study sites representing the contrasting surface morphologies of the selected urban and suburban stations.

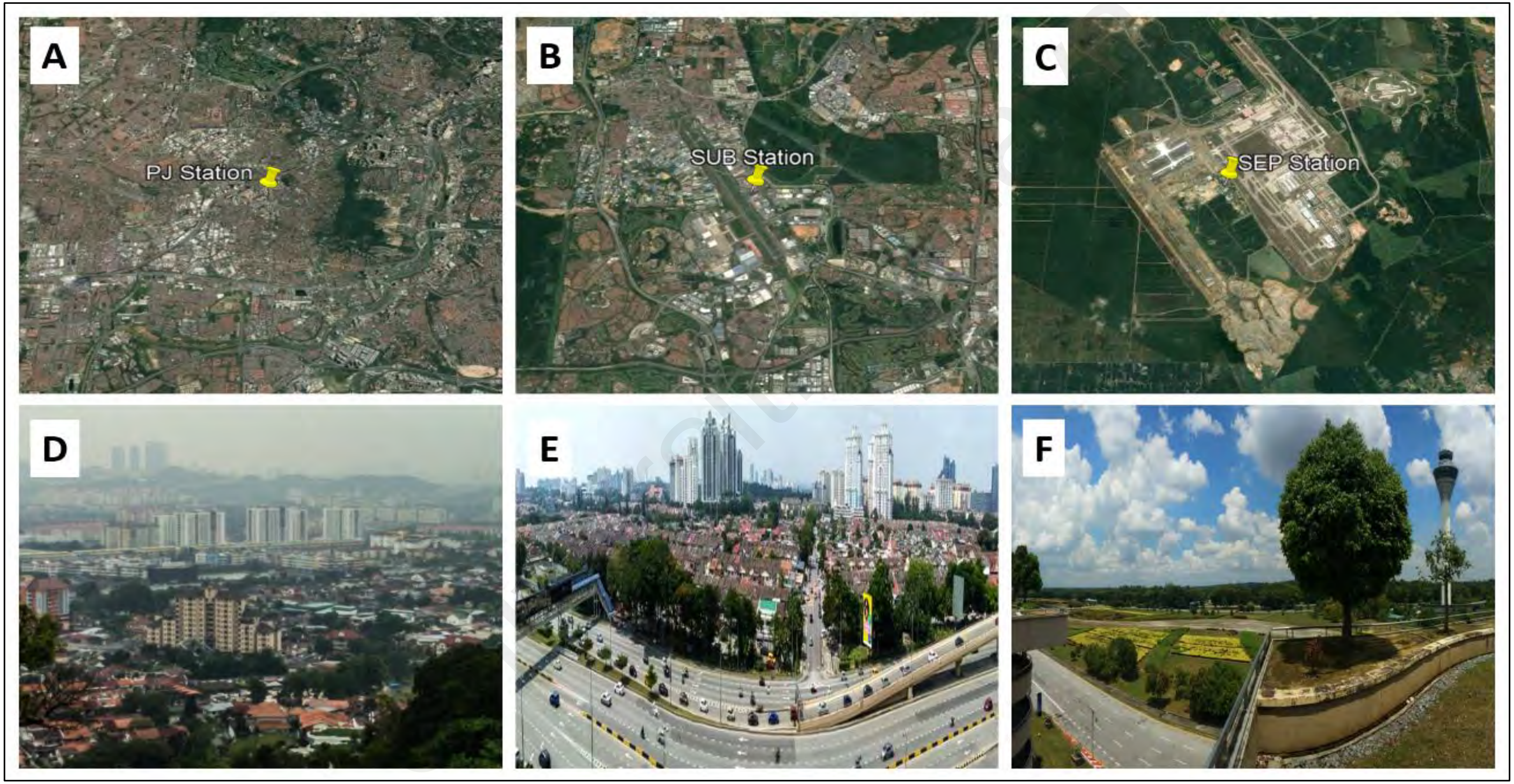


Figure 3.3: Study sites representing heterogeneous landscape morphology within 5 km radius from the meteorological observatories of MetMalaysia. (A & D) PJ station; (B & E) SUB station; (C & F) SEP station.

In brief, PJ station and SUB stations portray almost similar landscape structures with the majority of low- (1-3 storeys: 3-9 m) and mid-rise (4-9 storeys: 12-27 m) buildings interspersed with fewer numbers of high-rise (> 9 storeys: >27 m) buildings. On the other hand, the SEP station represents a different land cover with a significant portion of the pervious, vegetated landscape that enables it to be chosen as a reference suburban station. According to the Local Climate Zones (LCZ) scheme (Stewart and Oke, 2012), field observations revealed that both PJ and SUB stations represent a hybrid between compact low- and mid-rise built types whereas SEP station is sparsely-built and dispersed with dense vegetation. The land cover is mostly paved with asphalt, tar, and bricks in both urban stations whereas the suburban station consists of a sparse arrangement of low- and mid-rise buildings in a natural (vegetated) setting. The metadata of study sites is presented in Table 3.1.

Table 3.1: Metadata of study sites within 5 km radius from the meteorological observatories of MetMalaysia

Station (ID)	Coordinates	Altitude (m)	LCZ attributes	Characteristics
PJ (48648)	3°6'8.05" N; 101°38'41.4" E	60.80	Hybrid between compact low- and mid-rise buildings, interspersed with some high-rise buildings.	Adjacent to the heavy road network including the busiest Federal Highway; In the proximity of public facilities: UM Medical Centre, University of Malaya, MAHSA University and public schools; Next to Bangsar South commercial hub; Land cover paved with asphalt, tar and bricks; Buildings are mostly made up of concrete, iron, bricks and glass facades.
SUB (48647)	3°7'50.07" N; 101°33'8.78" E	16.64	Hybrid between compact low- and mid-rise buildings, interspersed with some high-rise buildings.	Congested commercial centres and road networks; Most residential areas of low- to mid-rise buildings; Shopping complexes and recreational centres; Commercial areas; Subang Air Port; Land cover paved with asphalt, tar and bricks; Buildings are mostly made up of concrete, iron, bricks and glass facades.
SEP (48650)	2°43'50.99" N; 101°42'11.47" E	16.11	Sparsely-built with dense vegetated area.	KLIA Airport; Dense vegetation comprises of natural forested areas, oil palm plantations and rubber estates; Traditional villages

Other than this, there are some additional criteria for the inclusion of these particular zones in this study as follows:

i. Firstly, all these three stations consist of simultaneously-operating integrated Automated Principal Weather Stations (APWS) of MetMalaysia which are designed in compliance with the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO) standards to fulfil international requirements for weather and climate monitoring.

ii. Secondly, meteorological variables are observed at the same time using instruments of similar range and resolutions for reliable comparisons to be made. Table 3.2 shows the description of the instruments used in data collection in the three meteorological observatories.

Table 3.2 : General description of the instruments used in meteorological data collection by meteorological observatories of MetMalaysia

Meteorological variable	Sensors/Brand	Resolution	Range
Temperature	PT100/JY 1000829	± 0.1 °C	-40-60 °C
Relative Humidity	HMP115/Vaisala HUMICAP®	± 1 %	0-100 %
Wind Speed & Direction	WAA151/Vaisala	± 0.5 m/s & ± 3º	0.4-75 m/s & 0-360º
Rainfall	Tipping Bucket/RIM-7499-BOM	± 0.2 mm	± 1%-200 mm/h
Atmospheric Pressure	PT300	± 0.2 hPa	800-1100 hPa

In particular, these three meteorological observatories are deployed with calibrated sensors to collect meteorological parameters at a height of 1.5 m above ground, except for the PJ station which is relocated on a rooftop of a four-story building (approximately 10 m) since early 2000. According to Jarraud (2008), such height is more than WMO's recommendations to site the meteorological instruments. However, studies by Oke (2004) and Chow and Roth (2006) clarified that temperature gradient errors should be negligible for the sensors placed more than 1 m height from the surface in densely built-up urban stations. In regards to this, assumptions are made that PJ station that satisfies similar urban morphology of the urban sites included in the aforementioned studies to display no vertical temperature gradients. To clarify this, vertical temperature gradient measurements are conducted at the PJ station's site from 12 p.m. to 2 p.m. and a very minimal mean temperature gradient of 0.035 ˚C per meter was recorded. In addition, the building rooftop where the instruments are located is covered with EPDM rubber (ethylene-propylene-diene monomer (M-class) rubber) to insulate and minimize heat exchange with the interior of the building.

iii. Thirdly, the stations are ensured to have minimal altitude variations to eliminate the influence of terrain differences on air temperature under the standard environmental lapse rate (0.64 °C drops per 100 m increase in altitude) (Siu and Hart, 2013). Since the altitude variations of the three stations are very small within 16-60 m, no empirical temperature corrections are performed in this study. Fourthly, the general land use within a radius of 500 m, from where the meteorological observatories are located, did not vary significantly in these stations, which represent the local-scale microclimate of that particular land use.

3.8 Meteorological data collection and time period justifications

Hourly (MYT: Malaysia Local Standard Time) meteorological data such as air temperature, relative humidity, wind speed and direction, atmospheric pressure and rainfall of the year 2016 are obtained from MetMalaysia for UHI analysis. In total, about 8,744 hourly datasets are acquired for each PJ, SUB and SEP station, respectively. The year 2016 is of particular interest in this study as GKL encountered many devastating consequences of rising temperatures such as flash floods, heat waves and even rare episodes of hail storms, which justify the imperative need of the current study to evaluate the status of temporal UHI of this year (Akasah and Doraisamy, 2014; Othman et al., 2016; The Star, 2016). Adding to this, United Nations declared 2016 as the hottest year ever on record after observing the mean global temperature of the first half of the year to be 1.3°C warmer than the late nineteenth century (United Nations (UN), 2016; Zhongming et al., 2020). Therefore, this study analyzed 2016's temperature profile and inherent UHII of the selected urban stations in GKL. In this study, one day is defined as 24-h period, starting from 12 a.m. to 11 p.m. to examine the diurnal cycles of the meteorological parameters, UHII and warming rates of the urban and suburban stations. Since there are no great variations in terms of instrumentation set-up, measurement height and data collection practices among the meteorological observatories, the homogeneity of the air temperature data is therefore warranted in this study (Wang and Shu, 2022).

3.9 Data collection and management

In reference to Velazquez-Lozada et al. (2006), meteorological datasets acquired under ideal meteorological conditions (112 calm and clear days in all the urban and suburban stations in a year) are only included in UHI analysis to avoid synoptic scale effects. Therefore, meteorological datasets recruited from MetMalaysia are processed by manually excluding the days with rainfall and moderate to strong winds (>6.00 m/s) according to Beaufort's scale, a widely used empirical measure to analyse and interpret the wind speed (Met Office, 2016). Previous observations have indicated that the threshold wind speed of 5 m/s could suppress mesoscale circulation generated by horizontal inhomogeneity with a patch length of 20 km and an effective surface sensible heat flux of about 250 W/m^2 (Lee and Baik, 2010). Furthermore, wind speeds <5 m/s are within the range proposed as ideal conditions to investigate UHIs (Kolokotroni and Giridharan, 2008; Park, 1986; Santamouris, 2015b). On the other hand, as described by Yang et al. (2012) and Wang et al. (2016), wet days are not included due to differences in heat fluxes between rainy and dry days. In particular, the accumulation of cloud cover before and after rain, as well as the subsequent evaporation process of rainwater, plays role in the removal of urban sensible and latent heat that might lead to an underestimation of UHII in the study areas (Jauregui, 1986; Li et al., 2011). Besides, the heating or cooling rate differences between urban and rural areas are also reported to be smaller during precipitation days that could result in weaker UHII (Lee and Baik, 2010). Such a scenario can lead to under-estimation of UHII in the urban areas. On this account, the hourly meteorological data collected on clear and dry days with stable atmospheric conditions (no abrupt changes in the local weather) in both urban and suburban stations are utilized to examine the temporal profile of UHI.

3.9.1 Treatment of missing data and outliers

It is undeniable that about 8,744 hourly datasets collected from the meteorological observatories for each station are comprised of some default data that show huge deviations from the average values (outliers). At the same time, there are some randomly missing data for certain meteorological parameters. However, it is worth mentioning that both of these cases only represent about 3.30% (for PJ), 0.09% (for SUB) and 0.14% (for SEP) of the overall datasets. Since the proportion of the default data is very small and negligible, the days that comprise such data are eventually excluded in the analysis (listwise deletion). As the remaining dataset is sufficiently large, it can be representative of the localized weather conditions of the urban and suburban stations.

3.10 Data analyses

3.10.1 The computation of UHII

The cleaned and processed data are used to compute hourly and monthly averages of relevant meteorological variables for the year 2016. For diurnal UHII computation, the one-year average hourly air temperature of the suburban station (SEP) was subtracted from that of the urban stations (PJ and SUB). Similarly, seasonal UHII was calculated by subtracting monthly average air temperature of the suburban station (SEP) from that of the urban stations (PJ and SUB). The equation (1) (Liu et al., 2007; Peng et al., 2022) is used to calculate UHII:

$$UHII = T_{urban} - T_{sub-urban} \qquad \text{Eq (1)}$$

where,

T = Average air temperature.

3.10.2 The computation of hourly cooling (warming) rate

As expounded by Oke (1982), cooling/warming rates of both urban and suburban stations are important indicators that drive the diurnal cycles of UHI. Hence, equation (2) (Lee and Baik, 2010; Pakarnseree et al., 2018) is used to calculate hourly cooling (warming) of both urban and suburban stations in this study:

$$Hourly\ cooling\ rate = \frac{\triangle T_{1-2}}{\triangle t_{1-2}} \qquad \text{Eq (2)}$$

where,

$\triangle T_{1-2}$ = Average air temperature differences between first and second observations.

$\triangle t_{1-2}$ = Time differences between first and second observations.

3.10.3 Statistical analyses

This section provides a description of the main statistical tests used in this study All the cleaned and finalized datasets are managed and analysed using IBM SPSS statistics version 23. The findings generated in all the tests are evaluated with 95% confidence interval ($p = 0.05$), unless stated otherwise. Two-tailed test of significance is selected in these tests.

3.10.3.1 Descriptive statistics

Descriptive analysis is performed by computing frequencies, percentages, minimum, maximum and average values for the meteorological parameters and UHII in the urban and suburban stations.

3.10.3.2 Testing the significant differences between the means of the meteorological variables using one-way analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) analysis

The one-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences between the means of independent (meteorological variables such as air temperature, wind speed and relative humidity) groups. The following key assumptions are satisfied during the test:

i. The data is continuous and normally distributed;
ii. There is no association between the data in each group or between the groups;
iii. The dataset comprises no significant outliers; and,
iv. The variance of the data in different groups must be homogeneous.

It should be noted that the one-way ANOVA test expresses whether the means of meteorological parameters between the PJ, SUB and SEP stations are significantly different without indicating which pair is different. Therefore, Tukey's HSD analysis is performed to identify the statistical difference between the pairs of urban and suburban stations according to the monsoon seasons.

3.10.3.3 Testing the influence of selected meteorological variables on UHII using Linear and Multiple Linear Regression analysis

The investigation on the possible influence of single independent variables (meteorological variables such as wind speed and relative humidity) on dependent variable (UHII) is carried out using Linear Regression analysis. Meanwhile, the combined influence of several meteorological variables on UHII are tested using Multiple Linear Regression analysis. A statistical metric known as the coefficient of determination (R^2) is computed as a measure of the variation in the dependent variable that can be explained by the variation in the independent variables. The multiple regression model is executed based on the following assumptions:

i. There is a linear association between the independent and dependent variables as shown by the scatterplot;
ii. No multicollinearity as the correlation between the independent and dependent variables is not too high;
iii. Residuals are normally distributed and satisfy multivariate normality; and,
iv. The data is homoscedastic with similar variance of error terms across the values of the independent variables.

3.10.3.4 Testing the strength of association between the meteorological variables and UHII using Pearson Correlation Analysis

The investigation on the statistical relationship and association between the selected independent (meteorological variables such as wind speed and relative humidity) and dependent (UHII) has been carried out by performing Pearson correlation analysis. Pearson correlation provides details on the magnitude (correlation coefficient, r) of the statistical association and the direction (+ or –) of the relationship, based on the method of covariance. The following assumptions are adhered during the test such as:

i. The tested relationships are independent to each other;
ii. The variables tested are linearly associated with each other when assessed via a scatterplot;
iii. The datasets comprised of no outliers; and,
iv. Homoscedasticity of the data is assumed and the variance is fixed throughout a distribution.

In this study, the direction and strength of association between independent and dependent variables are interpreted using the guide provided by Mukaka (2012). The correlation coefficients of 0.9 - 1.0 indicate 'very strong', 0.7 - 0.9 indicate 'strong', 0.5 - 0.7 indicate 'moderate', 0.3 - 0.5 indicate 'weak' and 0-0.3 indicate 'negligible' associations.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 Introduction

This chapter illustrates the main findings of the study and logical synthesis to support the primary outcomes reported in this study. UHI is defined as the temperature contrast between the urban and suburban/rural stations due to the differences in their energy balance (Ahmed et al., 2015; Benrazavi et al., 2016). As synoptic meteorological conditions regulate the formation of the UHI in the urban stations, fundamental analysis of the meteorological conditions of the study sites must precede the temporal analysis of UHIIs for a reliable assessment. Therefore, this chapter is organized into three main subsections that describe the temporal analysis of the meteorological variables, temporal variations of canopy-level UHII as well as the association between the selected meteorological variables and UHII in the urban stations in GKL.

4.2 Number of observations from the meteorological observatories included in the analysis for the year 2016

A careful selection of the days for observation of meteorological parameters is a prerequisite to generating a valid analysis of UHII in the urban stations (Steensen et al., 2022; Yang et al., 2020). Therefore, meteorological datasets from 112 calm and clear days that correspond to 2,688 hourly datasets in each of the selected urban and suburban stations in 2016 are included in the analysis to exclude the synoptic-scale effects of the extreme weather on local UHII (Velazquez-Lozada et al., 2006; Yang et al., 2020). In the context of this study, calm and clear days are defined after excluding days with daily accumulated rainfall of more than 0.1 mm and the day following the rainfall events to minimize the differences in heat fluxes between rainy and dry days (Rizvi et al., 2019;

Yang et al., 2012; Yang et al., 2020; Wang et al., 2016). On top of that, the days with moderate to strong winds (≥5.00 m/s) (Met Office, 2016) that could suppress mesoscale wind circulation and influence UHII are excluded from the analysis (Lee and Baik, 2010). Furthermore, wind speeds <5 m/s are only considered ideal to investigate UHIs (Kolokotroni and Giridharan, 2008; Santamouris, 2015b; Cuadrat et al., 2022). In terms of atmospheric pressure, minimal differences are observed between PJ (1,007.18 kPa), SUB (1,010.13 kPa) and SEP (1,009.79 kPa) stations. The influence of synoptic pressure patterns on the UHII is negligible and therefore excluded from further analysis. Table 4.1 illustrates the number of days used in the analysis according to the months and the monthly average air temperature of the analyzed days at the selected urban (PJ and SUB) and suburban (SEP) stations. As described in Table 4.1, the monthly average temperatures of PJ, SUB and SEP stations are comparatively stable from January to December with the atmospheric conditions of the days included for the observations representing the ideal conditions for UHI studies in GKL.

Table 4.1: The number of days used for the analysis from January 1 – December 31, 2016 and monthly average air temperature of the analyzed days

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
No. of days[a]	9	8	10	7	8	9	7	12	12	10	11	9	112
Average T_{PJ} (°C)[b]	30.18	29.76	30.70	30.97	29.77	30.02	29.53	29.90	29.36	29.20	28.74	28.92	29.75
SD_{PJ} (±)	2.68	2.32	2.80	2.84	2.57	2.41	2.36	2.85	1.87	2.14	2.09	2.57	2.60
Average T_{SUB} (°C)	29.01	28.83	29.74	30.34	29.70	29.46	29.02	29.55	29.04	29.02	27.72	28.50	29.16
SD_{SUB} (±)	2.97	2.96	3.29	2.87	2.31	2.65	2.48	2.52	2.06	2.72	2.37	2.18	2.90
Average T_{SEP} (°C)	28.84	28.51	29.25	29.55	28.89	28.33	28.38	28.26	28.36	28.45	27.36	28.19	28.53
SD_{SEP} (±)	2.74	2.68	2.98	2.82	2.35	2.41	2.05	2.72	2.13	2.24	2.18	2.25	2.66

[a] refers to the number of days after excluding the days with daily accumulated rainfall of more than 0.1 mm and the day following the rainfall events. The reported number of days included in the analysis for each months indicate clear and calm days with no rainfall events at all the urban (PJ and SUB) and reference (SEP) stations to enable reliable quantification of UHII.
[b] refers to the daily average air temperature of all the analyzed days at urban (PJ and SUB) and suburban (SEP) stations and SD refers to the standard deviation among the daily average temperatures of the days included in the analysis.

The highest monthly average temperatures for PJ (30.70 ± 2.80 °C), SUB (30.34 ± 2.87 °C) and SEP (29.55 ± 2.82 °C) stations are recorded in April, during the onset of the pre-southwest monsoon season. Meantime, the lowest averages in all the stations are recorded in November, a colder period associated with the northeast monsoon season. The annual average air temperature difference between the urban stations, PJ (29.75 ± 2.60 °C) and SUB (29.16 ± 2.90 °C), is relatively low (0.59 °C), indicating that these urban stations share similar thermal characteristics. Moreover, the annual average air temperature difference between the PJ-SEP pair is higher (1.22 °C) compared to the SUB-SEP pair (0.63 °C). This denotes that the average monthly temperature deviations between the PJ and SEP stations are more pronounced compared to the SUB and SEP stations. In addition, the standard deviations among the monthly average temperatures of the urban and suburban stations ranged from 1.87 °C to 2.85 °C for the PJ station, 2.06 °C to 3.29 °C for the SUB station and 2.05 °C to 2.98 °C for the SEP station, indicating that the climatic variations among the months are relatively moderate throughout the year.

It should be noted that the diurnal temperature range ($T_{max} - T_{min}$) of the urban stations in comparison with the reference suburban or rural stations usually incorporate the influences of meteorological variables on the energy balance of those stations (Yang et al., 2020). For instance, temperature observations during weak winds and cloudless skies often result in high daily maximum temperature and low daily minimum temperature due to strong solar heating after sunrise and enhanced longwave radiative cooling effects after sunset (Voogt and Oke, 2003). Hence, the UHII of the urban areas tends to be high under such meteorological conditions due to a slower cooling process compared to the rural peripheries in the late afternoon, especially after sunset (de Souza and dos Santos Alvalá, 2014). This is further explained in section 4.4.3 of this chapter with respect to the diurnal cooling rate differences between the urban and suburban stations. Since meteorological conditions tend to influence the formation and intensity of UHIs, the next section presents the temporal analysis of the meteorological variables in the selected urban and suburban stations in GKL.

4.3 Temporal analysis of meteorological variables in the selected urban and suburban stations in GKL

As the temporal variations of UHII are significantly modulated by the meteorological conditions of the study areas (Mathew et al., 2016; Steensen et al., 2022), this study presents a descriptive analysis of the temporal variations of meteorological conditions in the respective urban and suburban stations in the year 2016.

4.3.1 Temporal variations of average air temperature in the selected urban and suburban stations in GKL

The temporal evolution of average air temperature in the urban stations, PJ and SUB, in comparison to the reference suburban station, SEP is depicted in Figure 4.1. In general, the average air temperature exhibit similar trends in seasonal and diurnal variations in all the urban and suburban stations, indicating a clear and strong temporal distinction. As illustrated in Figure 4.1, the highest maximum temperatures are usually recorded during the northeast monsoon and the onset of pre-southwest monsoon seasons in all the stations. The maximum temperatures of 36.90 °C, 36.7 °C and 37.10 °C are observed in the month of April in PJ (average for April: 33.68 °C), SUB (average for April: 30. 51 °C) and SEP (average for April: 31.27 °C) stations, respectively. The lowest monthly average temperatures are usually recorded in the colder month of December in PJ (29.01 °C), SUB (28.45 °C) and SEP (28.23 °C) stations. Compared to both urban stations, the suburban SEP station recorded the lowest average temperatures in all the consecutive months in the year 2016, indicating that it is less warm compared to the urban stations. In terms of diurnal variations, both PJ and SUB stations recorded the maximum temperatures between the ranges of 36.4 - 36.9 °C during late afternoon hours (2 - 4 p.m.), when intense anthropogenic activities and solar radiation are at the peak in these urban centres. This indicates that both urban stations are relatively warmer than the reference SEP station, which recorded slightly lower maximum temperatures between the ranges of 35.3 – 35.6 °C during late afternoon hours (2 - 4 p.m.). It also should be noted that PJ and SUB stations are warmer than the SEP station before sunrise and in the late afternoon.

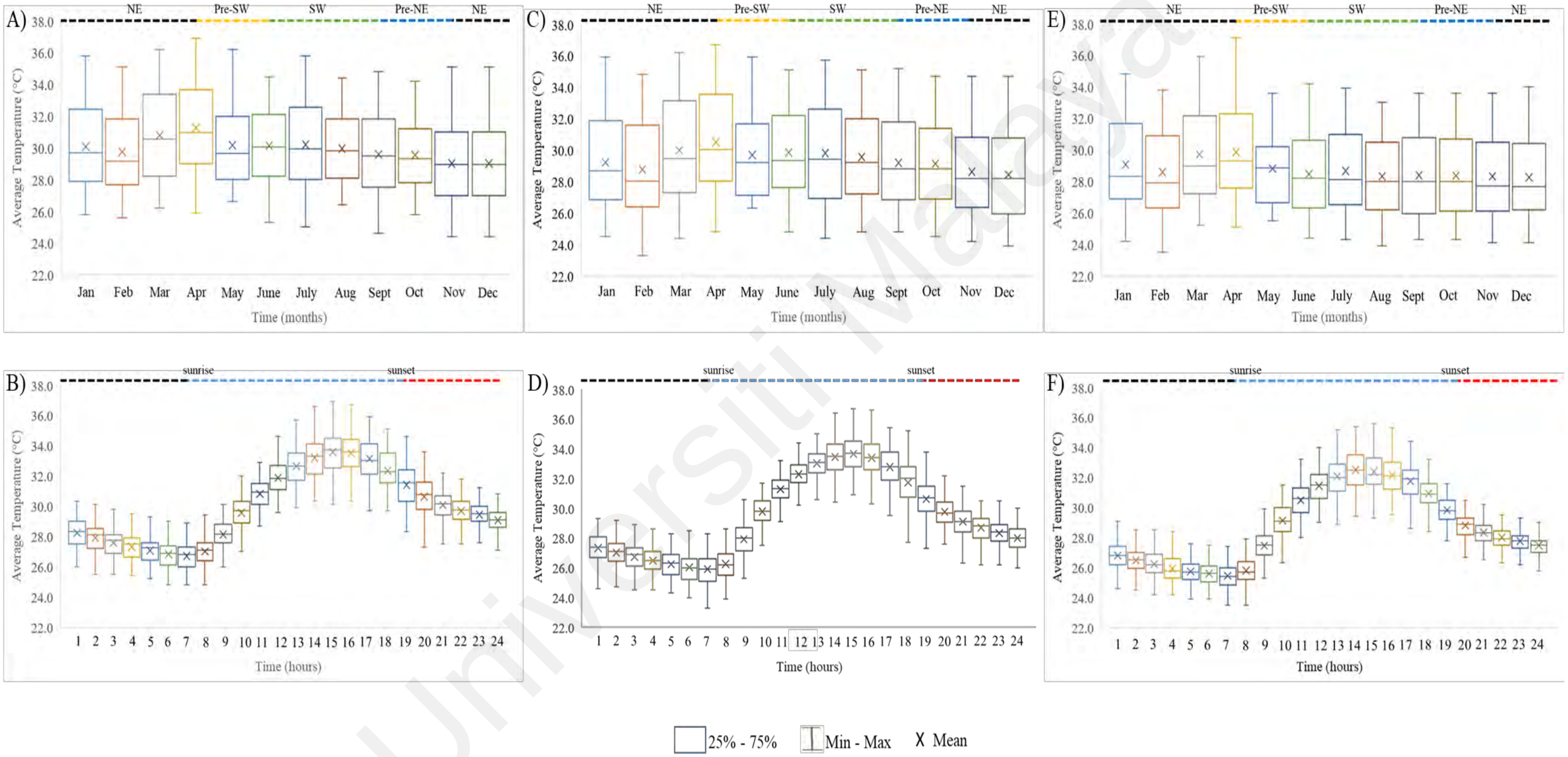


Figure 4.1: Variation of average air temperature (°C) in the selected urban and suburban stations of GKL: the variations in the average air temperature on a seasonal scale at (A) PJ station, (C) SUB station and (E) SEP station; the variations in the average air temperature on a diurnal scale at (B) PJ station, (D) SUB station and (F) SEP station, respectively.

A very minute hourly temperature difference is observed between urban and suburban stations from 9.00 a.m. until 12.00 p.m., with SEP station recording higher temperatures compared to both PJ and SUB stations. SEP station, which is sparsely built, is directly exposed to the intense solar radiation after the sun rises and gets warmer at the same rate as the urban stations. However, the heat loss (cooling rate) in SEP station starting from the late afternoon and the following hours is greater due to more open and exposed land structures compared to compactly built-up urban stations. Lacking thermally bulk concrete and man-made structures, pervious surfaces and reduced anthropogenic emissions in SEP station enable it to release the solar radiation at a much faster rate. Dense concrete jungles of both PJ and SUB stations trap the incoming solar radiation during the day and re-radiate it at night, potentially initiating the on-set of the UHI phenomenon.

On another note, PJ station, a vibrant site encapsulated by the north, west and east roads and also in the proximity to the busy Federal Highway as depicted in Figure 4.2, is always recorded the maximum average temperatures throughout the year, with the highest magnitude of 31.27 °C, observed during the onset of pre-southwest monsoon season. Other than the intense solar radiation, the persistence of high air temperatures in PJ station could be attributed to higher anthropogenic heat (heat flux density with human activity), emission loads liberated from vehicular exhausts, industrial and commercial activities, human metabolism and massive road infrastructures that trap and insulate the heat within the built environment. Since the exact heat flux is hardly quantifiable, many studies used proxy indicators such as distance to main roads, population density and proximity to urban areas to represent the anthropogenic factors (Kotharkar et al., 2019). With respect to the scope of the present study, no further attempts are made to quantify heat flux based on such proxy indicators to be associated with the UHI in this study. Therefore, even though the heat-generating factors are very prominent in the PJ station, explicit evidence and explanations of the relevant physical processes that cause the resultant UHI are limited to the observational data only in this study.

Figure 4.2: Enlarged aerial view of PJ station that is located in the middle of the busiest heavy road network

4.3.2 Temporal variations of average relative humidity in the selected urban and suburban stations in GKL

The seasonal and diurnal variation of average relative humidity (%) in PJ, SUB and SEP stations is illustrated in Figure 4.3. The maximum relative humidity of 96.00% and 97.00% are reported in December for PJ and SUB stations whereas the maximum relative humidity was observed in January for SEP station (94.00%). Nevertheless, it should be noted that PJ (72.25%), SUB (76.50%) and SEP (79.19%) stations recorded the highest average relative humidity in May during the pre-southwest monsoon. The lowest monthly average relative humidity is usually recorded in the months of February in PJ

(59.91%), SUB (66.06%) and SEP (64.82%) stations. As outlined in Figure 4.3, the longer boxplots during the northeast monsoon season in all the three stations indicated that the relative humidity data is more dispersed from January to April, thus explicating higher daily variability within this season. In contrast to the urbanized PJ and SUB stations, it is noteworthy that the SEP station, which retains a big portion of natural vegetation, recorded the highest average relative humidity values throughout the year.

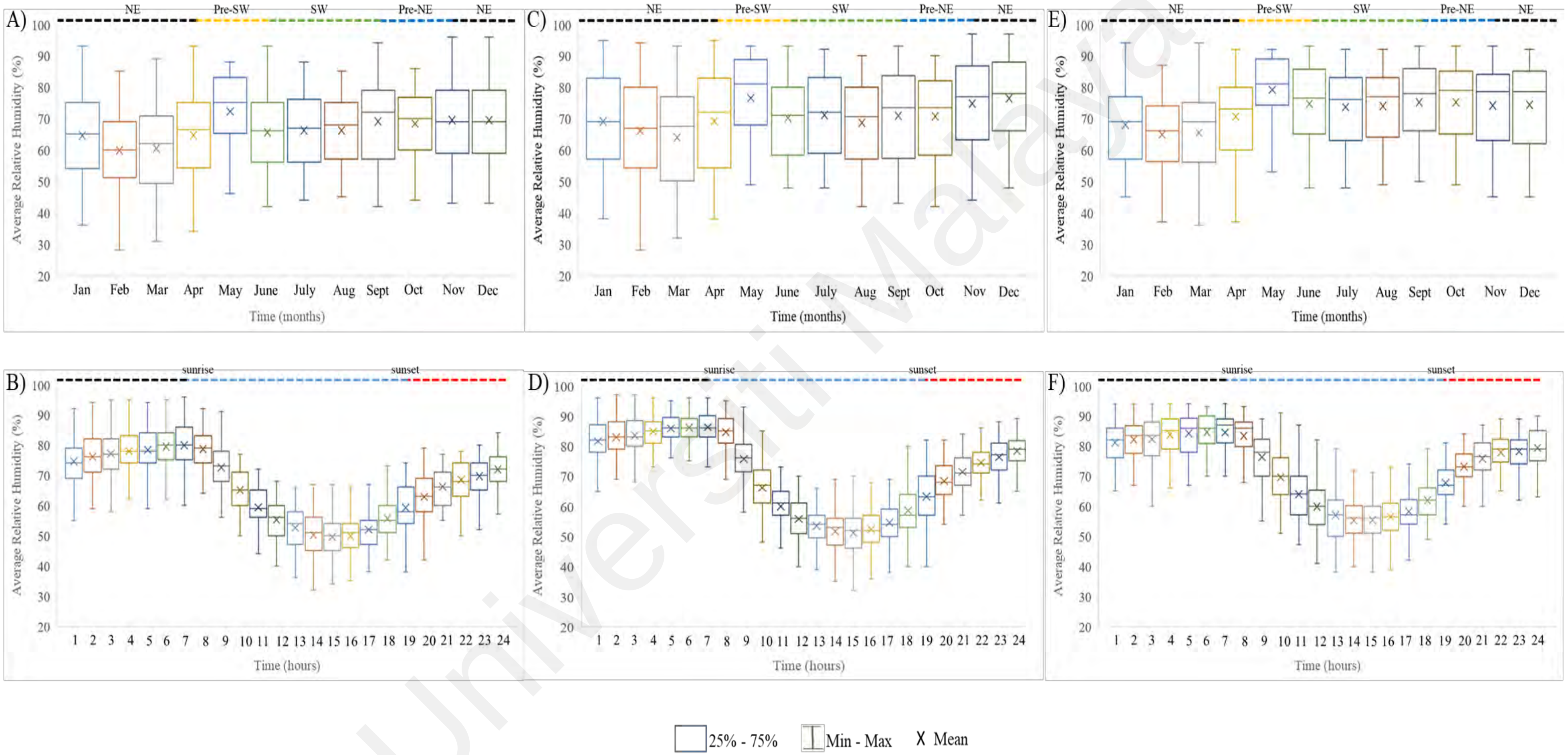


Figure 4.3: Variation of average relative humidity (%) in the selected urban and suburban stations of GKL: the variations in the average relative humidity on a seasonal scale at (A) PJ station, (C) SUB station and (E) SEP station; the variations in the average relative humidity on a diurnal scale at (B) PJ station, (D) SUB station and (F) SEP station, respectively.

Apart from this, the diurnal variation of relative humidity is inversely related to the diurnal variations of temperature as portrayed in Figure 4.1 (B, D and F) and Figure 4.3 (B, D and F). Similar diurnal variation is reported in a humid city, Lodz (Fortuniak et al., 2006). It can be easily deciphered that the diurnal relative humidity curve is completely opposite to that of the surface air temperature (Yang, Ren and Liu, 2013), with the higher values of relative humidity corresponding to the lower values of surface air temperature in a day or vice versa.

A gradual decline in average relative humidity is observed with increasing average temperatures, which starts about an hour after sunrise in all the stations. After that, the average humidity started to increase prior to a drop in the average temperature in the late afternoon, as observed at 3.00 p.m. On top of that, the pre-southwest, pre-northeast and northeast monsoon seasons registered the highest average relative humidity assemblages that can be associated with heavy monthly rainfall records in those seasons for all the stations as shown in Figure 4.4.

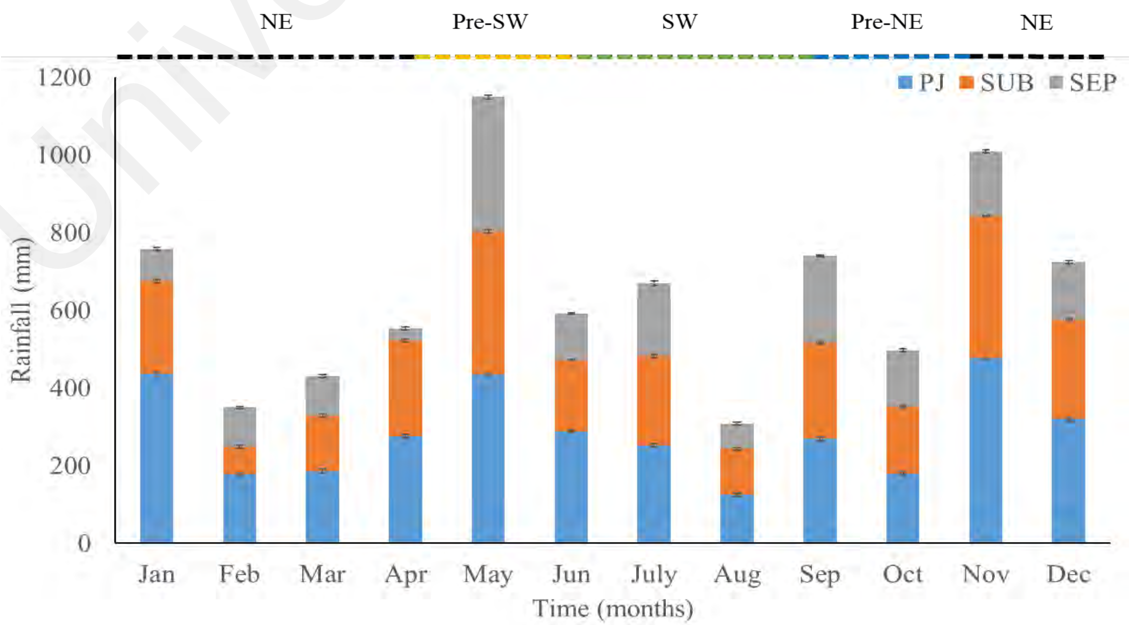
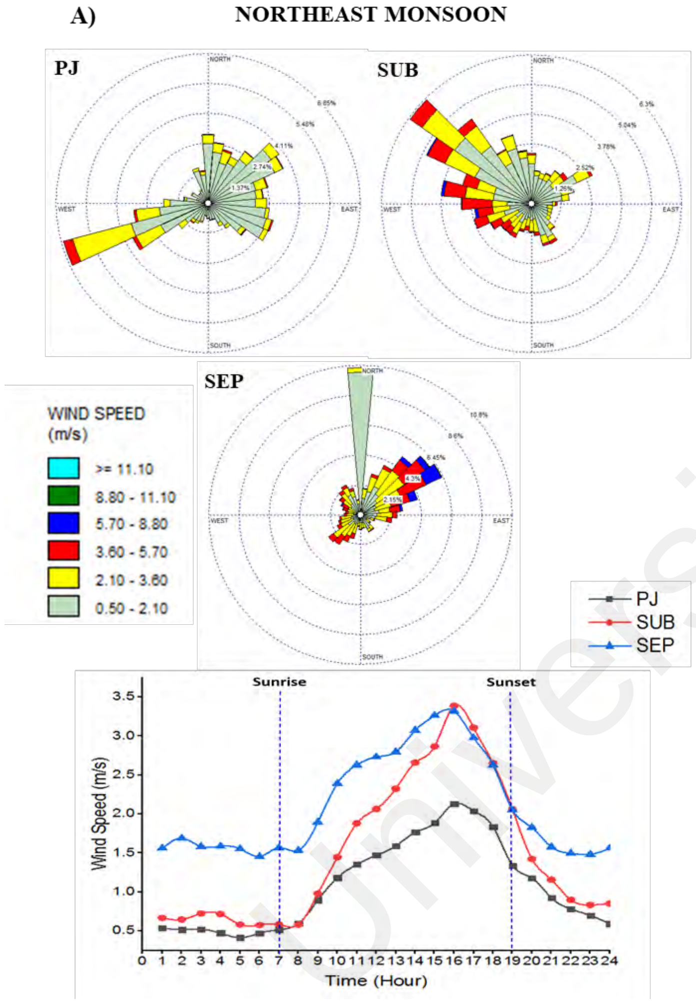


Figure 4.4: Monthly variations of average rainfall in the selected urban and rural stations of GKL

As displayed in Figure 4.4, the highest rainfall in PJ (435.20 ± 3.45 mm), SUB (367.48 ± 4.76 mm) and SEP (346.16 ± 4.81 mm) stations is observed during May which is associated with the pre-southwest monsoon. However, high cumulative rainfall events of all the stations exceeding 700 mm are recorded during the pre-northeast [September (739.60 mm)] northeast [January (758.32 mm), November (1009.46 mm), December (723.66 mm)] and pre-southwest [May (1148.84 mm)] seasons, respectively. It is evidenced that the rainfall events could reduce the urban temperatures that could lead to an underestimation of the temperature difference between urban-suburban pairs (He, 2018; Rizvi et al., 2019; Wang et al., 2016). For example, Rizvi et al. (2019) found that the maximum precipitation of 100 mm in 2016 has resulted in a gradual decline of the UHII up to 1.5 °C in Karachi, Pakistan. Indeed, rainfall is reported as one of the main controls of UHI effects in Bangkok, Thailand as the weakest UHII of 2 K is observed during the month with maximum precipitation whereas UHII of 5 K is recorded during the month with little precipitation (Arifwidodo and Tanaka, 2015). In another case of cities across North America, the climate model demonstrated that every 1 mm reduction in annual precipitation could increase UHII by 0.0021 K (Zhao et al., 2014). A similar mitigation effect of rainfall is reported on the UHII in Jining, China, with the highest mitigation role observed during the summer season compared to the other seasons (Wang et al., 2016). As the inclusion of days with rainfall events can result in the underestimation of UHII, the rainfall days are eventually excluded in the analysis reported in this thesis. Hence, there is no inferential analysis made on the rainfall trend or its influence on UHII in GKL. Nonetheless, it should be noted that some studies have provided contrary findings to this whereby UHI is associated with increased precipitation in the urban area. The accumulation of warm air in the urban area elevates the cloud formation that brings more rainfall events in the urban areas (Dou et al., 2015; Liu and Niyogi, 2019; Steensen et al., 2022).

4.3.3 Temporal variations of average wind speed in the selected urban and suburban stations in GKL

The seasonal and diurnal profile of the wind pattern is displayed in Figure 4.5 by highlighting the speed and frequency of wind blowing from respective cardinal directions. By referring to modern Beaufort's scale (Met Office, 2016), PJ, SUB and SEP stations experience 99.30%, 93.80% and 88.50% episodes of calm winds (≤ 4.00 m/s) respectively during the northeast monsoon season, with the prevailing winds from the northeast direction, except for the SUB station. The wind is mostly blowing from the northwest direction in the SUB station. During the southwest monsoon season, the calm wind is predominantly blowing from the southeast direction in all the stations (PJ: 80.30%, SUB: 93.20 %, SEP: 96.10%) at speeds between 0-4.00 m/s. Overall, approximately more than 90% of the wind from all these stations is relatively calm (0-4.00 m/s) under stable atmospheric conditions. Meanwhile, there is a mixed wind direction pattern observed during both short inter-monsoon seasons. On the diurnal scales, a similar periodic behaviour is observed in all the stations. The SEP station always records the highest wind speed among the three stations in all the four monsoon seasons, especially before sunrise and after sunset. Apparently, higher wind speed is always observed in the SUB station compared to the SEP station during the late afternoon before continuing to decrease after the sunset. Conversely, PJ records the lowest wind speed during all the seasons compared to the other two stations.



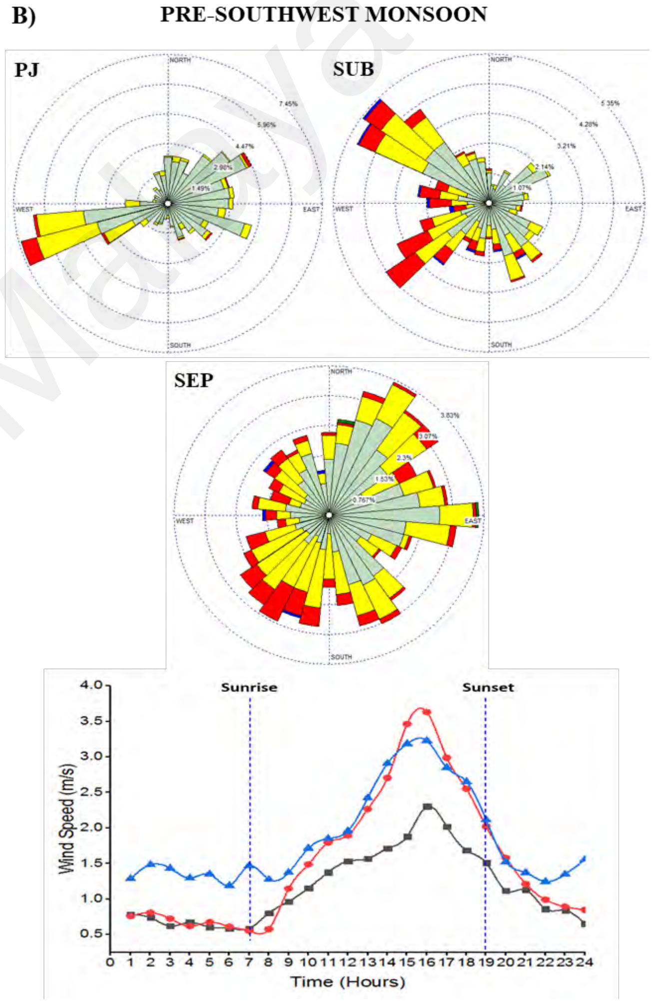


Figure 4.5: Variations of seasonal wind directions and diurnal wind speed in the selected urban and suburban stations of GKL: (A) Northeast monsoon; (B) Pre-southwest monsoon; (C) Southwest monsoon; (D) Pre-northeast monsoon

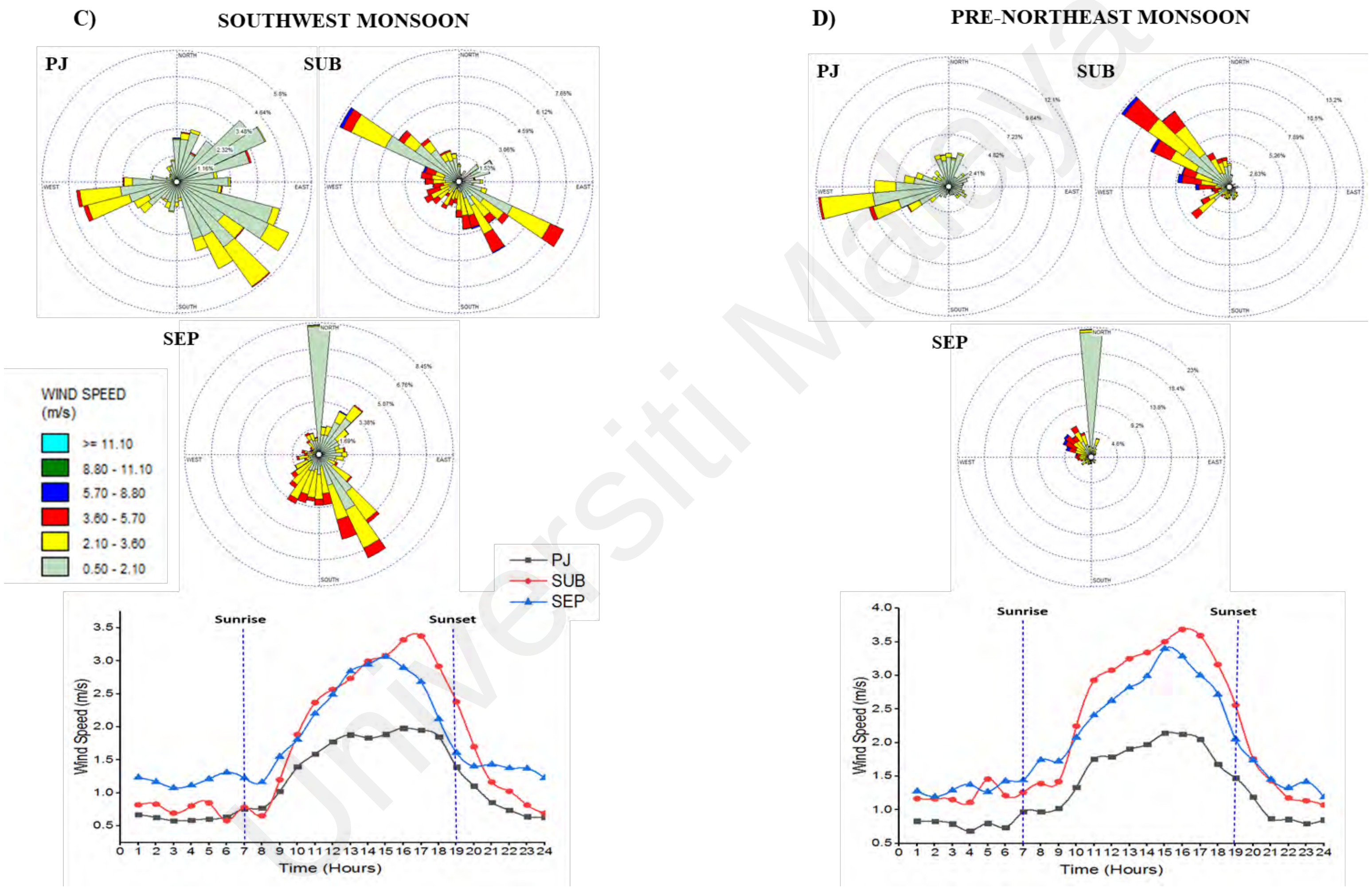


Figure 4.5 (continuation) Variations of seasonal wind directions and diurnal wind speed in the selected urban and suburban stations of GKL: (A) Northeast monsoon; (B) Pre-southwest monsoon; (C) Southwest monsoon; (D) Pre-northeast monsoon

As indicated in Figure 4.6, seasonal average wind speed ranges between 1.54 ± 0.45 to 2.56 ± 0.94 m/s, 1.45 ± 1.04 to 2.20 ± 1.30 m/s and 1.05 ± 1.09 to 1.35 ± 1.22 m/s in SEP, SUB and PJ stations, respectively. There are apparent seasonal variations in the average wind speed of SUB and SEP stations whereas such variations are insignificant in the PJ station. Even though the average wind speed in the SEP (suburban) station is the highest during the period of January to April compared to the SUB station, no significant differences were observed from September to December. As discussed by Park (1986) and Santamouris (2015b), the average wind speed in both urban and suburban stations is lower than the reported threshold wind speeds (4.00 -11.00 m/s) that able to decrease the UHII. On top of that, most of the wind speeds included in the analysis are within the range proposed as ideal conditions (<5 m/s) to investigate UHIs (Kolokotroni and Giridharan, 2008). Essentially, the average wind speeds in all the selected zones are mostly calm and gentle which ensures the feasibility of most of the data sets to be incorporated in the UHI analysis in the later part.

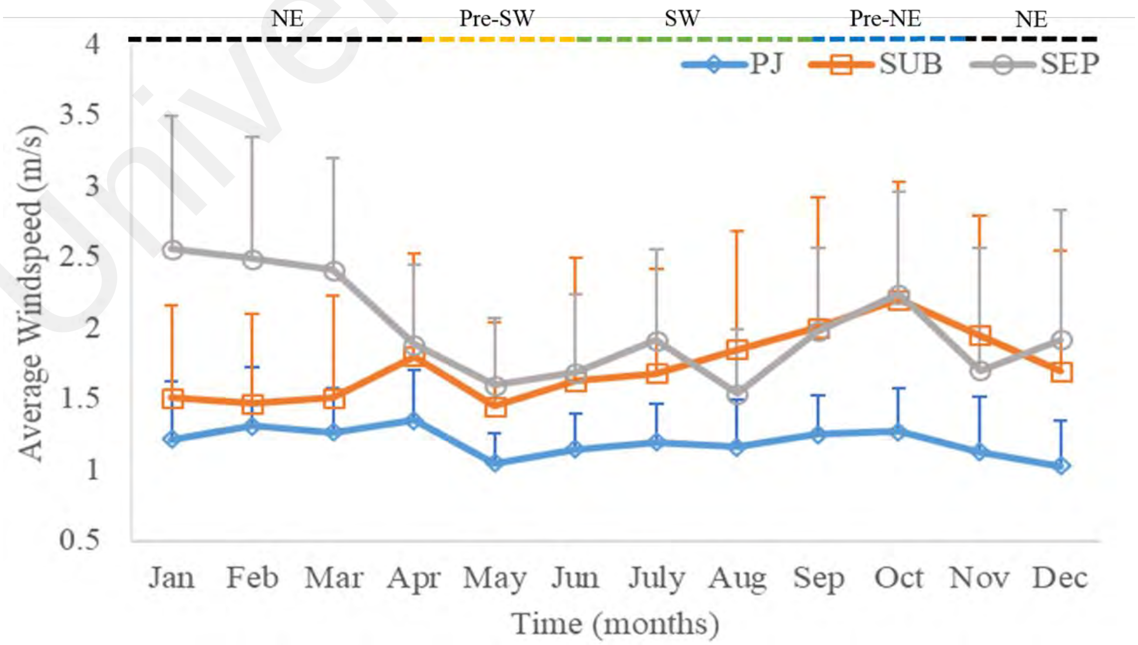


Figure 4.6: Variations in seasonal average wind speed in the selected urban and suburban stations of GKL

4.3.4 The mean difference between the selected meteorological variables of the urban and suburban stations

The mean difference between the selected meteorological variables of the urban and suburban stations is computed using a one-way analysis of variance (ANOVA) according to the monsoon seasons. According to the ANOVA computations, there is a statistically significant difference between the means of the selected meteorological variables at the 95% confidence interval [$F(2,33) = 11.135$, $p = 0.000$]. The statistically significant difference in the mean of the meteorological variables is subjected to post-hoc comparisons to elucidate the statistical difference between the pairs of urban and suburban stations according to the monsoon seasons. Table 4.2 displays the results of post-hoc comparisons of means of selected meteorological parameters between the urban and suburban stations using Tukey's HSD (honest significant difference) test.

From the results, it can be concluded that the mean difference in the average temperature, relative humidity and wind speed are mostly statistically distinct ($p < 0.05$) between the PJ, SUB and SEP stations during the southwest monsoon season. This provides an early prediction that high magnitudes of UHI can be expected during this season in both PJ and SUB stations. The difference between the mean of the average temperature of the PJ-SEP pair is statistically significant during northeast ($p = 0.045$) and southwest monsoon ($p = 0.001$) seasons whereas the SUB-SEP pair registers statistical significance during southwest monsoon ($p = 0.002$) only. Meanwhile, it is noteworthy that there are no significant differences in the means of temperature observed among the PJ-SEP and SUB-SEP pairs during the intermediate monsoon seasons. As described in Table 4.2, the amplitude difference of seasonal average relative humidity is significant between the PJ - SEP pair ($p = 0.001$), SUB - SEP ($p = 0.0034$) and PJ - SUB ($p = 0.0029$) during the dry period associated with the southwest monsoon season.

Table 4.2: Post-hoc comparisons of means of selected meteorological parameters between the urban and suburban stations using Tukey's HSD (honest significant difference) test

Stations	Meteorological parameters	Monsoon Seasons							
		NE Monsoon		Pre-SW Monsoon		SW Monsoon		Pre-NE Monsoon	
		Q Statistic	p-value	Q Statistic	p-value	Q Statistic	p-value	Q Statistic	p-value
PJ - SEP	Average T	4.037	**0.045***	2.635	0.292	11.344	**0.001****	2.099	0.413
	Average RH	3.369	0.094	1.893	0.470	8.743	**0.001****	2.523	0.252
	Average WS	4.878	**0.018***	2.397	0.340	7.244	**0.002***	6.251	**0.011***
SUB - SEP	Average T	1.092	0.718	1.833	0.488	7.742	**0.001****	0.916	0.799
	Average RH	0.167	0.900	0.743	0.859	4.299	**0.034***	0.777	0.839
	Average WS	3.926	**0.051***	0.083	0.900	0.286	0.900	0.026	0.900
PJ - SUB	Average T	2.945	0.148	0.802	0.839	3.602	0.073	1.183	0.709
	Average RH	3.202	0.113	1.151	0.719	4.443	**0.029***	1.746	0.479
	Average WS	0.952	0.772	2.480	0.323	7.530	**0.001****	6.225	**0.011***

** refers to the statistical significance at $p < 0.001$; * refers to the statistical significance at $p < 0.05$

4.4 Temporal variations of canopy-level UHII in the selected urban stations in GKL

In general, UHII is referring to the temperature differences between the urban (PJ and SUB) and the reference suburban (SEP) or rural stations (Ahmed et al., 2015; Półrolniczak et al., 2017). As the term 'rural' does not represent most of the vernacular GKL, the suburban SEP station that demonstrates different degrees of development, growth and its position which is far from the urban clusters is selected for the comparison (Ezber et al., 2007; Memon et al., 2011). In this section, an analysis of the temporal variations of UHII according to the seasonal and diurnal patterns in both PJ and SUB urban stations is described for the year 2016.

4.4.1 Seasonal variation of canopy-level UHII in the selected urban station GKL

4.4.1.1 Seasonal variation of canopy-level UHII in PJ Station

The perceptible positive thermal contrast between PJ and SEP stations under ideal synoptic weather conditions is illustrated in Figure 4.7, corroborating the genesis of the UHI effect with varying intensities throughout the monsoon seasons in this study. The daily UHIIs for 112 days are averaged for each month and also expressed as the yearly average UHII for the year 2016. The yearly average of the UHII for the year 2016 in the PJ station is 1.25 °C. The monthly averages of UHII range from 0.74 °C (December) to 1.70 °C (June), with the highest magnitude recorded during the hot days associated with the southwest monsoon season. It is noteworthy that the monthly average UHIIs during the pre-southwest and southwest monsoon seasons (from April to August) are higher than the yearly average UHII in the PJ station. In the cooler months associated with the northeast monsoon, the monthly averages of the UHII are lower than the yearly average UHII. Although there are no large variations in the monthly averages of UHII in the PJ station, the maximum of the daily average UHII can reach up to 4.4 °C as reported in March.

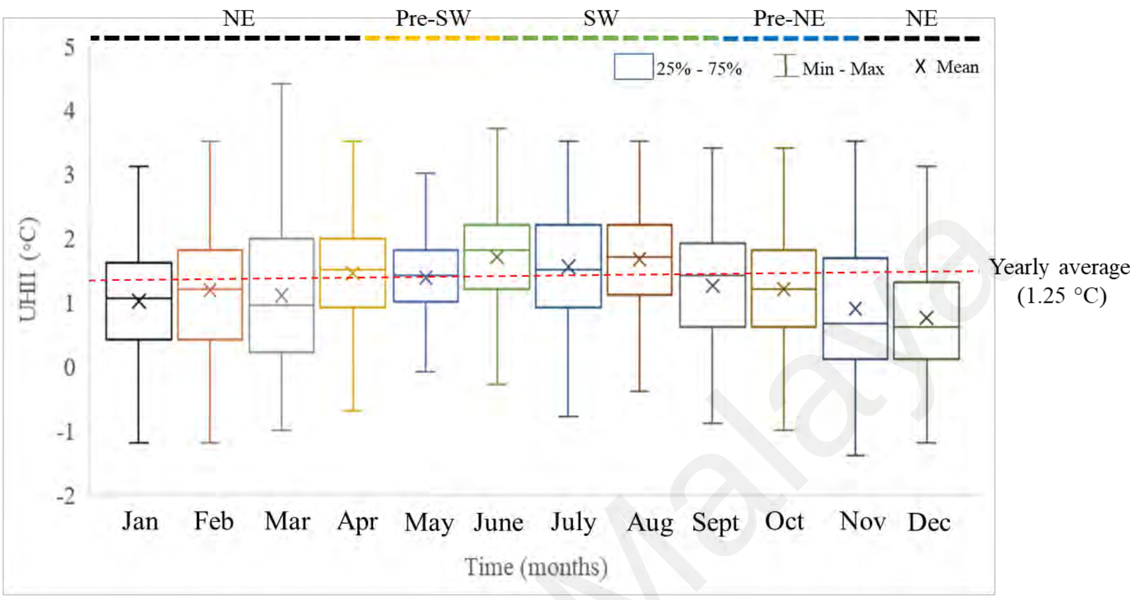


Figure 4.7: Seasonal variations of canopy-level UHII in PJ station

4.4.1.2 Seasonal variation of canopy-level UHII in SUB station

The seasonal variation of canopy-level UHII in the SUB station in reference to the SEP station is depicted in Figure 4.8. The yearly average of the UHII for the year 2016 in the SUB station is 0.67 °C. The monthly averages of UHII range from 0.15 °C (January) to 1.40 °C (June). Similar to the PJ station, the highest magnitude of average UHII for the SUB station is registered during relatively drier months associated with southwest monsoon seasons. Likewise, the monthly average UHIIs during the pre-southwest and southwest monsoon seasons (from April to September) are higher than the yearly average UHII in the SUB station. Besides, the month of June also recorded the highest maximum of the daily average UHII of 3.1 °C.

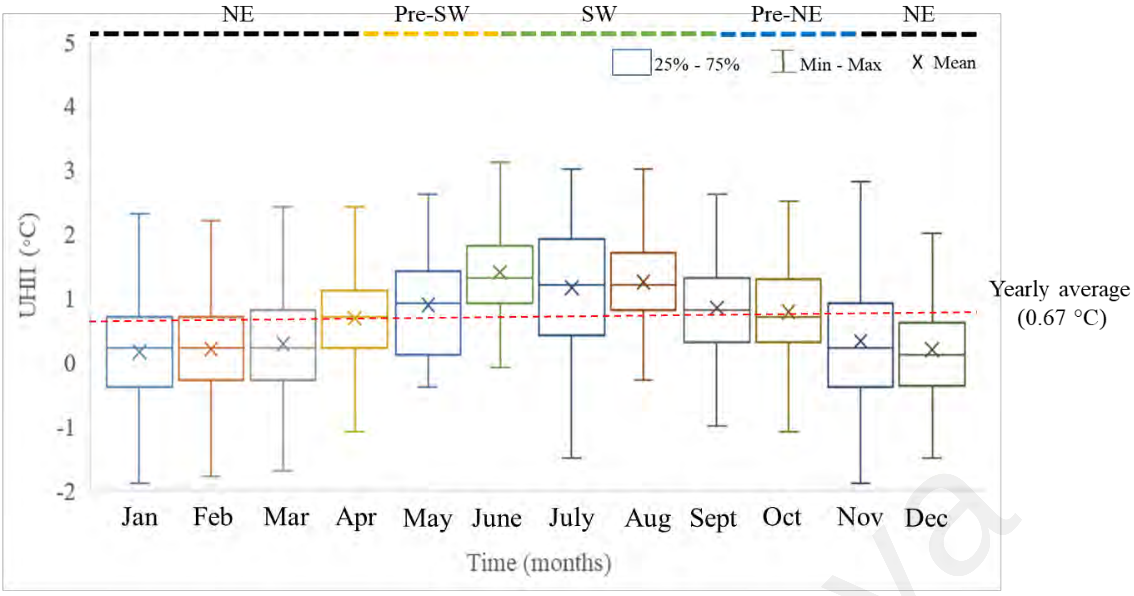


Figure 4.8: Seasonal variations of canopy-level UHII in SUB station

In summary, both urban stations display almost similar seasonal trends despite prominent variations in the magnitudes of the monthly average UHIIs. In addition, the PJ station records the highest UHIIs in every month compared to the SUB station. In both urban stations, monthly average UHIIs exceeding the yearly average UHII are usually observed during drier months associated with pre-southwest and southwest monsoon seasons from April to August. The conclusion that can be drawn from this scenario is that UHI in both PJ and SUB stations is more pronounced during the hot and drier months associated with the southwest monsoon season. It is worth mentioning that there is an obvious fluctuation in the monthly average UHIIs of both PJ and SUB stations during this period where a drop is registered between June and July before it rises again in August and continues to decrease again due to the impacts of seasonal features. Interestingly, an inverse fluctuating relationship (negative correlation) is observed among relative humidity (Figure 4.3), rainfall (Figure 4.4), wind speed (Figure 4.6) and the currently discussed UHII of both urban stations between June to August, indicating a possible relationship between these meteorological variables and UHIIs of these urban stations.

Low monthly average UHIIs are usually observed during wet, pre-northeast and northeast monsoon seasons between October to March in both urban stations.

Though little, the seasonal UHII trends observed in this study are commensurate with the results obtained by the previous studies conducted in other tropical regions characterized by hot and humid climatic conditions. For instance, Chow and Roth (2006) observed the highest UHI magnitude (7.07 °C) within commercial areas during the dry, southwest monsoon season in Singapore. Similarly, Amorim and Dubreuil (2017) identified the highest UHII (4.1 °C) during the drier months of April and July with the lowest precipitation records in Brazil. In another study conducted in Chang-Zhu-Tan urban agglomeration that experiences a subtropical monsoon climate, Wang et al. (2020) identified that the maximum magnitudes of SUHI can reach up to approximately 2.5 °C in Zhuzhou, especially during the summer season.

Interestingly, high UHII are also recorded during dry, summer nights in some upper latitude countries with cold climates. For instance, Klysik and Fortuniak (1999) observed the greatest UHII between 3 and 4 °C to occur during summertime in Lodz, Poland. Likewise, Kolokotroni and Giridharan (2008) witnessed high daytime UHII of 8.9 °C under ideal synoptic weather conditions in the semi-urban area of London in summer. The UHII in Zaragoza, Spain under calm atmospheric situations is more intense during summer (2.5 °C per hour) than in winter (2.2 °C per hour), which is limited by wind speeds exceeding 10 km/h and disappeared with wind speeds over 50 km/h (Cuadrat et al., 2022). Even though the highest seasonal UHII are usually recorded during the hot and dry seasons in both climates, the intensities recorded in this study are relatively lower compared to the aforementioned studies.

Notwithstanding a clear temporal pattern of UHII in both dry and wet seasons across climate zones, it should be noted that the seasonal variations of UHII could be synergistically influenced by some natural phenomena (i.e. heat waves, El Niño and La Niña) and human-induced disasters (i.e. haze episodes and urban aerosol pollution islands) (He et al., 2021; Kemarau and Eboy, 2021; Li et al., 2020; Rizvi et al., 2019). The occurrence of the above-mentioned events could lead to the amplification and reduction in the magnitudes of UHII. Such a scenario could cause deviations in the normal behaviour of UHII with seasons. In an attempt of examining the relationship between UHI and heatwaves, Rizvi et al. (2019) discovered that the UHII was 2.5 times higher on heat wave days than on non-heat wave days in Karachi. In another case, Li et al. (2020) revealed a negative correlation between the urban aerosol pollution island and UHI in summer and claimed that UHI mitigation accelerated the concentration of PM_{10} by 3%. In Kuching, Sarawak, Kemarau and Eboy (2021) spotlighted that El Niño and La Niña events that are associated with the El-Niño Southern Oscillation (ENSO) influence the LST and UHI magnitudes up to 30 °C. In regards to this, cautions must be practised when conducting UHI assessments during the occurrence of the aforementioned events to recognize, understand and interpret any deviations from the regular temporal behaviour of UHII in the tropical and temperate regions.

4.4.2 Diurnal variation of canopy-level UHII in the selected urban station GKL

4.4.2.1 Diurnal variation of canopy-level UHII in PJ station

The hourly UHIIs for the 112 days are averaged for 24 hours for the PJ station and displayed in Figure 4.9. The daily average of the UHII in the PJ station is 1.19 °C. The hourly averages of UHII range from 0.34 °C (11 a.m.) to 1.78 °C (8 p.m.), with the magnitudes surpassing the daily average usually recorded before sunrise (1 a.m. to 7 a.m.) and from late afternoon (3 p.m. onwards) until the midnight (12 a.m.). In particular, the

PJ station recorded the highest hourly average UHII of 1.78 °C at about 8 pm after sunset. The hourly average UHIIs below the daily average are recorded after sunrise (7 am) until late afternoon (2 p.m.). The hourly UHII magnitudes exceeding -1 °C are mostly reported from 9 am to 2 p.m., indicating the occurrence of urban cool islands during this period with the maximum intensity of -4.01 °C at 2 p.m. Besides, the maximum hourly average UHII can reach up to 5.6 °C as observed at 8 pm in PJ station. It is important to note that the PJ station registered a positive hourly average UHII in a day, which indicates the air temperature at urban stations is always higher compared to that of the suburban station.

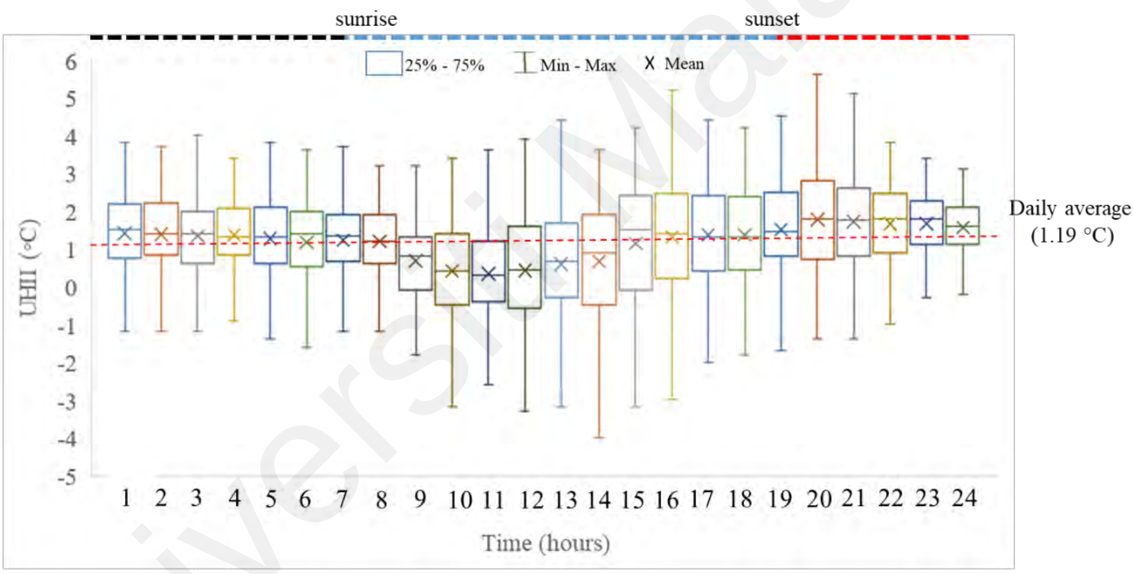


Figure 4.9: Diurnal variations of canopy-level UHII in PJ station

4.4.2.2 Diurnal variation of canopy-level UHII in SUB station

The hourly UHIIs averaged for 24 hours for the SUB station are portrayed in Figure 4.10. The daily average of the UHII in the SUB station is 0.73 °C. The hourly averages of UHII range from 0.45 °C (6 a.m.) to 1.26 °C (3 p.m.). In contrast to the PJ station, the hourly UHII exceeding the daily average is usually recorded from 11 a.m. until 10 p.m. In addition, the hourly UHIIs below the daily average are recorded from 1 a.m. to 10 a.m. as well as from 10 p.m. to 12 a.m. The highest hourly average UHII of

1.26 °C is recorded at 3 p.m. The maximum hourly average UHII can reach up to 4.0 °C as observed at 4 pm at the SUB station. Unlike PJ station, the maximum intensity of the urban cool islands (-1.8 °C) is rather smaller and observed at 9 a.m., 5 p.m. and 6 p.m., respectively.

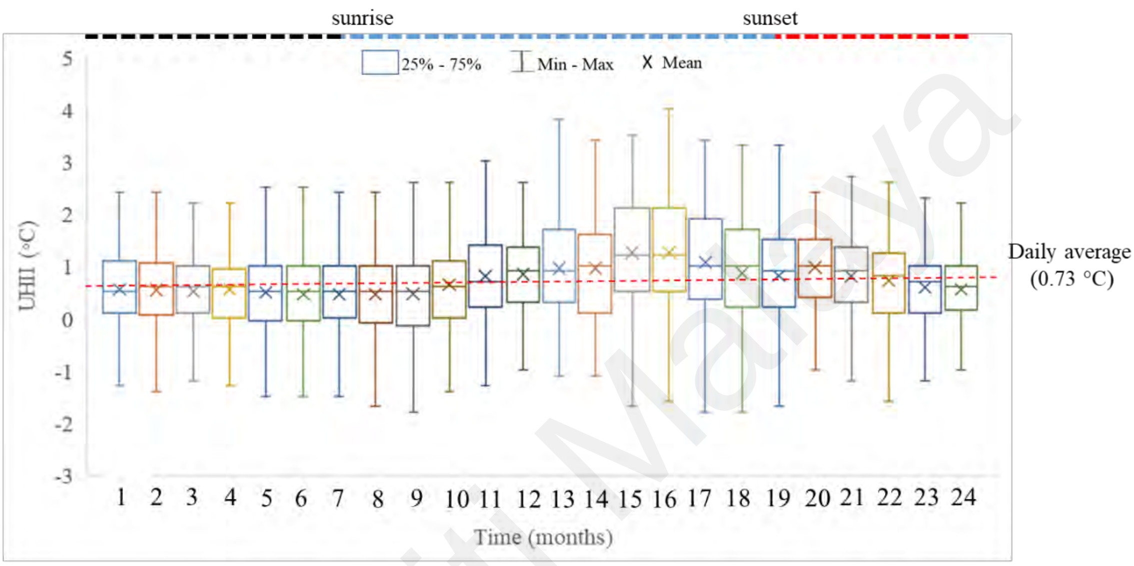


Figure 4.10: Diurnal variations of canopy-level UHII in SUB station

To summarize, it can be said that both PJ and SUB stations registered positive hourly average maximum UHII that indicates the air temperature at urban stations is always higher compared to the suburban station. Nonetheless, the highest hourly average UHII in PJ station is recorded at 8 p.m. after sunset whereas a contrasting diurnal pattern is observed in SUB with the highest hourly average UHII is recorded at 4 p.m. In fact, the variation of hourly average UHII amplitudes between both PJ and SUB stations is noticed to be large, up to 0.86 °C before sunrise and 1.08 °C after sunset. Such a big difference in UHII between these urban stations at nights and early mornings reveals that the nocturnal UHI phenomenon is more pronounced in PJ station. This is in agreement with the findings of Eastin et al. (2018) who reported high average nocturnal UHII up to 2.24 °C to occur either after sunset or near sunrise in a rapidly growing, subtropical city of

Charlotte, North Carolina. Likewise, de Souza and dos Santos Alvalá (2014) observed a distinct diurnal pattern of UHII (annual average of 3.00 °C) with two high-intensity peaks observed at two time frames of the diurnal cycle, one at 8.00 a.m. and another one between 3.00 p.m. and 5.00 p.m. in Manaus, Brazil. In addition, such findings can be attributed to varying degrees of urban metabolism and traffic activities at different time frames in both stations. As discussed earlier, a meteorological observatory in PJ station, which is located adjacent to a heavy, network of busy roads with unceasing traffic activities until late night accumulates and concentrates anthropogenic heat and smoke exhausts from vehicular emissions that can be possibly related to the amplification of the air temperature around the station. The meteorological observatory of SUB station is designated for aviation purposes and located in an open space, a little far from the compact building structures concentrated in the centre of SUB station. Such a physical land structure that is quite different from that of the PJ meteorological observatory could cause the observed variations among the UHII recorded in the SUB station. However, this range seems to be smaller during the daytime, approximately one hour after the sunrise until late afternoon.

4.4.3 Cooling (warming) rates of urban and suburban stations in GKL

The magnitude and diurnal variations of canopy-level UHII are highly accredited to the nocturnal cooling rate differences between densely-built urban areas and less-built rural peripheries (Roth, 2013). The slower nocturnal cooling rate of the urban areas due to the presence of heat-retaining urban materials is responsible for the detection of UHI compared to the outer suburbs (de Souza and dos Santos Alvalá, 2014; Pakarnseree et al., 2018). In line with this, the present study attempted to examine the cooling rate differences between the study areas that correspond to the formation of UHI. Of note, the cooling (warming) rates of the urban and suburban stations are calculated by subtracting the temperature value of a particular hour (e.g. 7 a.m.) from the temperature value of the succeeding hour (e.g. 8 a.m.) for all the 24 hours in a day. The averaged hourly cooling (warming) rates of the urban (PJ and SUB) and suburban (SEP) stations over 24 hours are plotted in Figure 4.11.

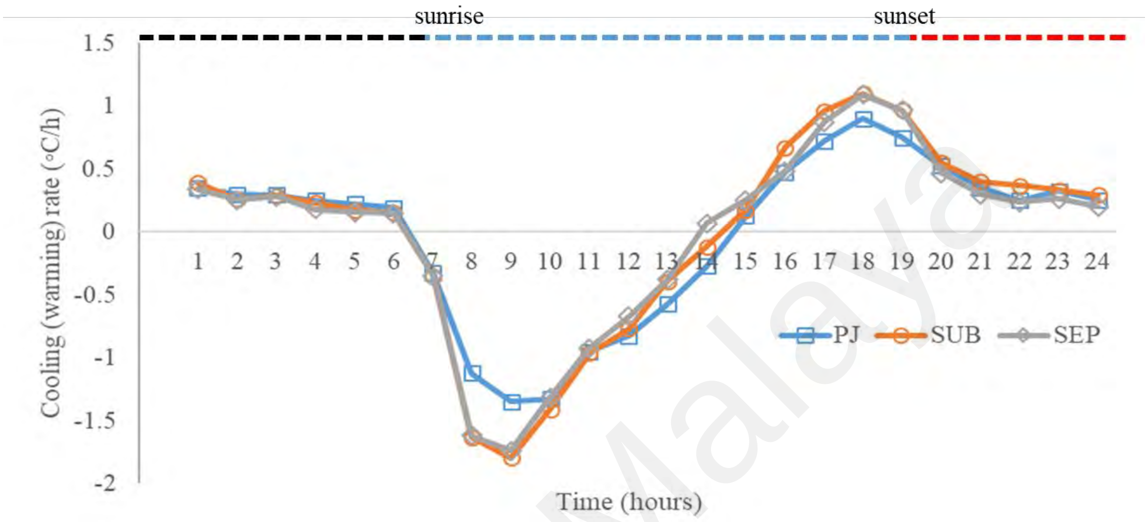


Figure 4.11: Cooling (warming) rates of urban and suburban stations in GKL

As indicated in Figure 4.11, the temperature contrast between a particular hour and the succeeding hour in the urban and suburban stations are increasing after sunrise (7.00 a.m.) until 9.00 a.m., thus projecting a decreasing cooling rate trend within this period. However, the hourly temperature deviations are reduced after these hours as the urban and suburban stations started to receive intense solar radiation, causing an upward trend. It should be noted that the temperature differences between the consecutive hours in the PJ station are relatively low from 7 a.m. – 11 a.m. compared to the SUB and SEP stations. This indicates that SUB and SEP stations are getting warmer faster compared to the PJ station within this timeframe possibly due to the land use pattern, which is open and less compact compared to the PJ station. All the stations started to get warmer after 9 a.m. and started to cool down after 6 p.m. On an important note, the highest cooling rate in SUB (1.10 °C/h) and PJ (0.90 °C/h) is reached around 6 pm. Moreover, the cooling rate of the SUB station (0.18 - 1.10 °C/h) is higher than that of the PJ station (0.13 – 0.90 °C/h) from late afternoon to night (3 p.m. - 12 a.m.). The findings of the low cooling rate of the PJ station correspond to the high magnitudes of the nocturnal UHII in the PJ station compared to the SUB station. The reduced cooling rates of the PJ station are likely to be caused by the degree of urbanization represented by the density and height of buildings, heavy traffic network and anthropogenic heat emissions that lead to increased heat absorption by the urban fabric and consequently result in the development of the UHI (Ramakreshnan et al., 2019).

On the other hand, the cooling rate of SEP station is the lowest from 8 p.m. -12 a.m. (0.20 – 0.47 °C/h) and from 1 - 6 a.m. (0.15 – 0.34 °C/h). In response to this, SEP station tend to release heat faster than the PJ and SUB stations, justifying the possible reasons for the development of nocturnal UHI with varying intensities in these urban stations. Indeed, this can also be attributed to the faster emittance of long-wave radiation at the suburban station compared to the urban stations due to more heat absorption and storage within the urban canyons (Makokha and Shisanya, 2010). Similar observations are also reported in Manaus city, Brazil where the maximum cooling rates for the urban and rural areas are found at 6.00 p.m. (−1.25 °C/h) and at 5.00 p.m. (− 0.68 °C /h). In the city of Charlotte, North Carolina, which shares a humid subtropical climate, the maximum urban and rural cooling rates are observed within a few hours of sunset with larger rural maxima preceded by 1-2 h the urban maxima (Eastin et al., 2018). The dissimilar cooling rates between urban and suburban or rural stations can be attributed to urban heat storage that maintains a positive sensible heat flux after sunset. Such behaviour indicated that the urban areas cool down slowly in comparison to the rural areas due to the urban surface properties (de Souza and dos Santos Alvalá, 2014). As indicated in Figures 4.9 and 4.10, peak UHII values are observed in the late evening a few hours before or after the sunset, indicating that the UHI phenomenon tends to be nocturnal. It also needs to be noted that the cooling at all the urban sites starts around 2-3 p.m., slightly later than that observed at the suburban station (1-2 p.m.). From this, it can be clearly inferred that the growth of UHI occurs as the SEP station cools at higher rates than those observed at urban sites from late afternoon until sunset. The diurnal UHI attains a maximum intensity when rural and urban cooling rates become almost equal in magnitude around one hour after sunset for PJ station and around late afternoon for SUB station. After sunrise, the SEP station, which is sparsely built experiences much higher warming compared to the urban stations, resulting in a rapid decrease of UHI intensity throughout the morning hours.

This is further supported by the warming rate differences between the PJ and SEP stations as shown in Figure 4.12. The highest warming rate difference between the PJ and SEP stations can reach up to 0.50 °C/h as observed at 8 a.m. Positive warming rate differences between the PJ and SEP stations are recorded mainly one or two hours before sunrise and after sunset, indicating that the PJ station is warmer compared to the SEP station during this period. In addition, positive warming rate differences are observed for 14 hours corresponding to 58.33% hours of UHI phenomena in a day. Such a scenario can be attributed to the high nocturnal UHIIs above the daily average recorded at the PJ station. On top of that, this finding elucidates that the UHI is primarily a nocturnal phenomenon and is caused by differences in the nighttime cooling rates between urban and its reference suburban or rural stations.

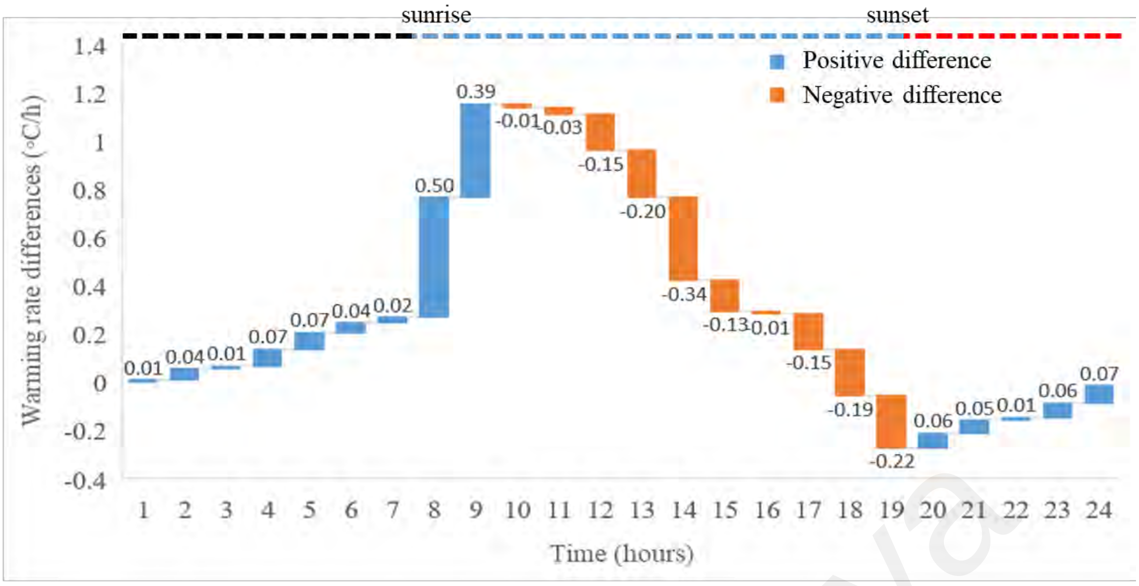


Figure 4.12: The warming rate differences between PJ and SEP stations

As shown in Figure 4.13, the warming rate differences between SUB and SEP stations exhibit a similar trend to that between the PJ and SEP stations. Notwithstanding this pattern, the difference is only observed in terms of the time period in which the positive and negative warming rate differences are recorded. For SUB-SEP pairs, the positive warming rate differences are recorded after 3 p.m. and before sunrise (7 a.m.), possibly justifying the reasons for the high hourly average UHII recorded during these hours in the SUB station. The highest warming rate difference between SUB and SEP stations can reach up to 0.18 °C/h as observed at 4 p.m. Unlike PJ-SEP pairs, the highest warming rate difference of SUB-SEP pairs is rather smaller (difference of 0.32 °C/h) and the positive warming rate differences persist for 16 hours, which correspond to 66.67% of urban heating phenomena in a day.

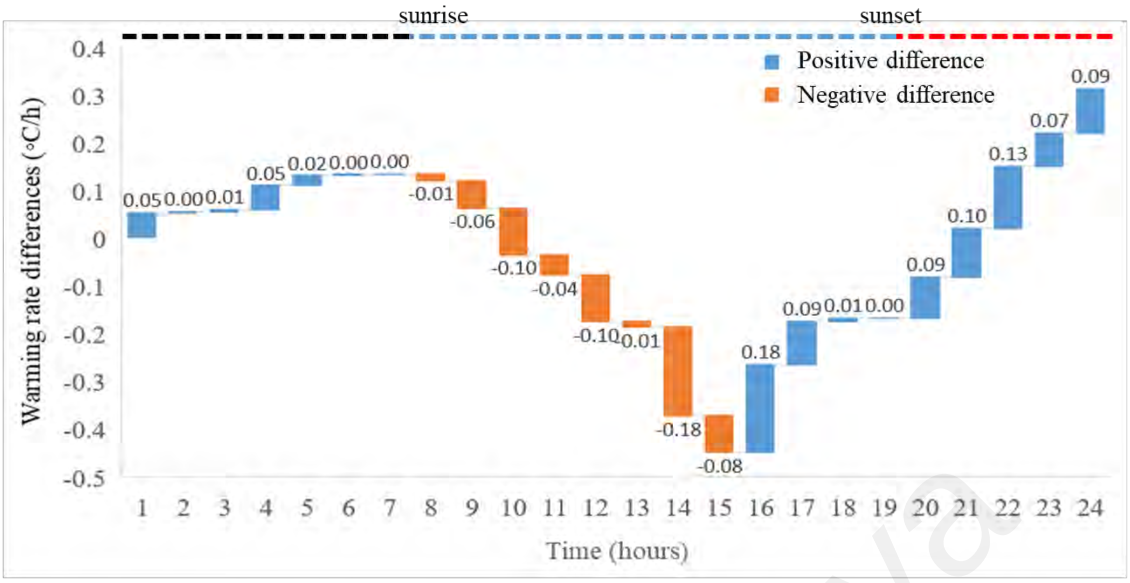


Figure 4.13: The warming rate differences between SUB and SEP stations

In this study, hourly cooling (warming) rates in both urban stations are comparatively steady from the night (9 p.m.) until early morning (6 a.m.) as also reported in the neighbouring tropical country, Singapore, by Chow and Roth (2006) using similar approaches. The findings of Pakarnseree et al. (2018) in Bangkok, Thailand, another neighbouring country with a similar climate, also recorded similar observation whereby the urban areas had slower cooling rates than their surrounding vicinities between 4 p.m and 10 p.m. On top of that, this observation is more eminent during clear days of winters and summers in comparison to rainy seasons. In addition, the highest cooling warming rates recorded in PJ station (0.90 °C/h) and SUB station (1.10 °C/h) are approximately similar to the one observed in Singapore and proportionately smaller than the one observed in another tropical city, Mexico (1.80 °C/h) (Jauregui, 1986). Such disparities in urban cooling rates between climatically similar cities in different geographical zones, are reminiscent of the influence of topography, elevation and corresponding synoptic meteorological elements on heat dissipation from the urban areas. Indeed, this area still needs more scholarly studies to provide more in-depth insight into the influence of geographical features on the urban heating phenomenon.

4.4.4 Frequency distribution of the UHII classes in the selected urban station GKL

As most of the peak UHII in urban stations are observed in late evenings for PJ station and late afternoon for SUB station, this section evaluated the frequency distribution of hourly UHII at both daytime (7 a.m. -7 p.m.) and night-time (7 p.m. - 7 a.m.). The frequency of hourly UHII events classified according to the days, nights and monsoon seasons at the PJ and SUB stations is presented in Table 4.3. It is apparent that the hourly UHIIs between 1-3 °C occur the most at night during all the monsoon seasons. In particular, UHII of more than 3 °C during the hottest and driest southwest monsoon season occur the most (5.52 %) during the nights in PJ station compared to the daytime (4.58 %). In the case of the SUB station, about 9.28% of the UHI events more than 2 °C are attributed to the nighttime compared to the daytime (5.94%). These findings further validate that high UHIIs are more pronounced at nights compared to the daytime.

Table 4.3: Frequency of hourly UHII events classified according to the days and nights at the urban stations in GKL

Seasons	UHII Classes	Stations			
		PJ-SEP		SUB-SEP	
		Day	Night	Day	Night
		n (%)	n (%)	n (%)	n (%)
NE Monsoon	≤ -3	0 (0)	0 (0)	0 (0)	0 (0)
	(-3, -2]	0 (0)	0 (0)	0 (0)	0 (0)
	(-2, -1]	10 (1.16)	3 (0.35)	27 (3.31)	23 (2.82)
	(-1, 0]	111 (12.85)	12 (1.39)	114 (13.19)	119 (13.78)
	(0, 1]	159 (18.40)	147 (17.01)	202 (23.38)	193 (22.34)
	(1, 2]	102 (11.81)	161 (18.63)	72 (8.33)	88 (10.19)
	(2, 3]	41 (4.75)	85 (9.84)	14 (1.62)	8 (0.93)
	> 3	9 (1.04)	24 (2.78)	3 (0.35)	1 (0.12)
Pre-SW Monsoon	≤ -3	0 (0)	0 (0)	0 (0)	1 (0.28)
	(-3, -2]	0 (0)	0 (0)	7 (1.94)	5 (1.39)
	(-2, -1]	25 (6.94)	4 (1.11)	24 (6.67)	4 (1.11)
	(-1, 0]	22 (6.11)	7 (1.94)	31 (8.61)	20 (5.56)
	(0, 1]	49 (13.61)	37 (10.28)	47 (13.06)	52 (14.44)
	(1, 2]	51 (14.17)	78 (21.67)	54 (15.00)	79 (21.94)

Table 4.3 (cont.) : Frequency of hourly UHII events classified according to the days and nights at the urban stations in GKL

	(2, 3]	24 (6.67)	46 (12.78)	16 (4.44)	19 (5.28)
	> 3	9 (2.50)	8 (2.22)	1 (0.28)	0 (0)
SW Monsoon	≤ -3	0 (0)	0 (0)	0 (0)	0 (0)
	(-3, -2]	2 (0.21)	17 (1.77)	0 (0)	0 (0)
	(-2, -1]	5 (0.52)	9 (0.94)	17 (1.77)	1 (0.10)
	(-1, 0]	22 (2.29)	15 (1.56)	49 (5.10)	13 (1.35)
	(0, 1]	127 (13.23)	74 (7.71)	175 (18.23)	130 (13.54)
	(1, 2]	152 (15.83)	171 (17.81)	182 (18.96)	181 (18.85)
	(2, 3]	128 (13.33)	141 (14.69)	50 (5.21)	83 (8.65)
	> 3	44 (4.58)	53 (5.52)	7 (0.73)	6 (0.63)
Pre-NE Monsoon	≤ -3	1 (0.20)	0 (0)	0 (0)	0 (0)
	(-3, -2]	5 (0.99)	0 (0)	12 (2.38)	4 (0.79)
	(-2, -1]	11 (2.18)	8 (1.59)	16 (3.17)	3 (0.34)
	(-1, 0]	21 (4.17)	14 (2.78)	14 (2.78)	22 (4.37)
	(0, 1]	79 (15.67)	65 (12.90)	85 (16.87)	63 (12.50)
	(1, 2]	94 (18.65)	97 (19.25)	103 (20.44)	132 (26.19)
	(2, 3]	33 (6.55)	56 (11.11)	19 (3.77)	27 (5.36)
	> 3	8 (1.59)	12 (2.38)	3 (0.60)	1 (0.20)

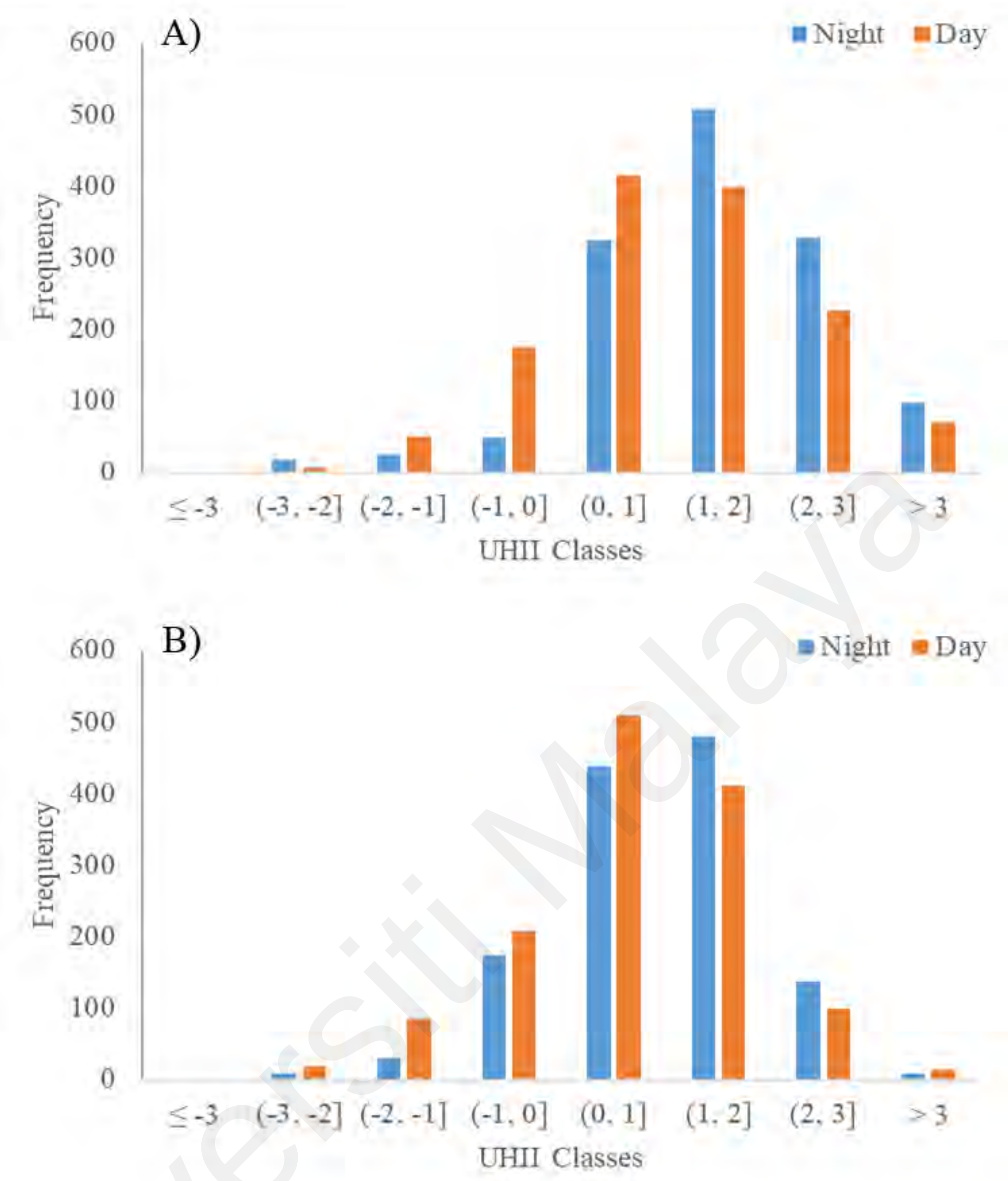


Figure 4.14: Distribution of the frequency of occurrence of UHII during daytime and nighttime in urban stations of GKL. (A) PJ station; (B) SUB station.

Figure 4.14 demonstrated the distribution of the frequency of occurrence of UHII during daytime and nighttime in PJ and SUB stations. The temperature differences between the urban stations and their suburban surrounding are evenly distributed among the considered UHII groups during both daytime and nighttime. Nonetheless, the nighttime UHI effect is more pronounced compared to the daytime effect, and this finding is consistent with the theory of urban energy balance discussed by Oke (1988) and corroborates that UHI is a nocturnal phenomenon (Kim and Baik, 2002; van Hove et al., 2015). A greater number of nocturnal UHI events in PJ and SUB stations are within 1-2 °C at night whereas diurnal UHI events are greatest within 0 - 1 °C in both urban stations. However, the SUB station also recorded high daytime UHII which is tally with the findings of Amorim and Dubreuil (2017) who observed the occurrence of highest UHII during the day-time in tropical settlements of Brazil.

4.5 Association between selected meteorological variables and UHII in the selected urban station GKL

The diurnal variability of the UHII in the urban stations is highly influenced by the local weather conditions (He, 2018; Wang et al., 2016). For instance, the building envelope and other urban structures could influence the wind speed and direction as well as shortwave and long wave radiation balances that impose a significant influence on UHII (Kotharkar et al., 2019). While evidence to verify the aforementioned association is quite plentiful in the temperate climatic countries, more in-depth analysis is required to quantitatively endorse such responses in the context of tropical countries. In a broader context, such analysis is vital to corroborate whether the canopy-level UHII of the urban stations in different climatic zones manifests distinct responses to the same meteorological parameters. In response to this, the relationship between the average daily UHII, average relative humidity and average wind speed for the 112 days at the PJ and SUB stations is studied as shown in Figure 4.15. Pearson correlation analyses are performed to explore the influence of these synoptic meteorological variables on temporal UHII. For PJ and SUB stations, both relative humidity (Figure 4.15 A & C) and wind speed (Figure 4.15 B & D) were showing moderate negative correlations with the UHII recorded in those sites.

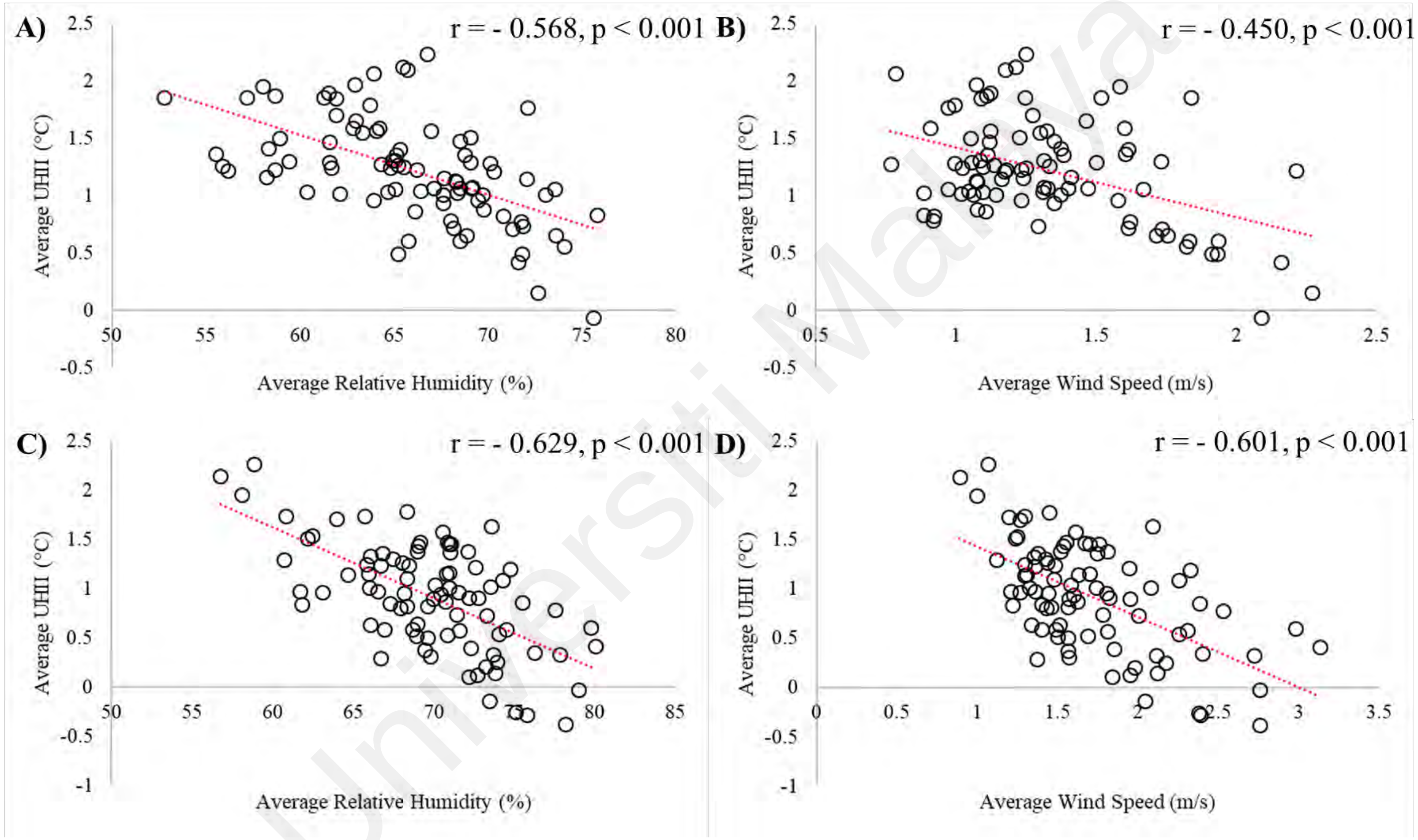


Figure 4.15: Linear regression of UHII with relative humidity and wind speed: (A&B) PJ station; (C&D) SUB station

Meanwhile, Figure 4.16 describes the relationship between the average change in the hourly UHII (△UHII) with the hourly changes in the relative humidity (△relative humidity) and hourly changes in the wind speed (△wind speed) at the PJ and SUB stations. To achieve this, the differences between the average hourly UHII are tested in response to the differences between the respective hourly changes in the meteorological parameters. For PJ and SUB stations, the average change in the hourly relative humidity (Figure 4.16 A & C) and the average change in the hourly wind speed (Figure 4.16 B & D) were showing moderate negative correlations with the average change in the hourly UHII recorded in those sites.

It is important to note that all the possible non-linear relationships between the average UHII with the corresponding meteorological parameters, including exponential, logarithmic, polynomial and power functions are examined during the regression analysis. However, these functions did not yield a significantly better fit to the data compared to the line of best fit presented by the linear functions. As moderate correlations are obtained between the daily average UHII and the meteorological variables, the combined influences of relative humidity and wind speed on UHII are tested in the Multiple Linear Regression model as tabulated in Table 4.4. The key outcomes of the multiple linear regression analysis and the correlation analysis that are statistically significant at $p < 0.001$ for both PJ and SEP stations are displayed in Table 4.4.

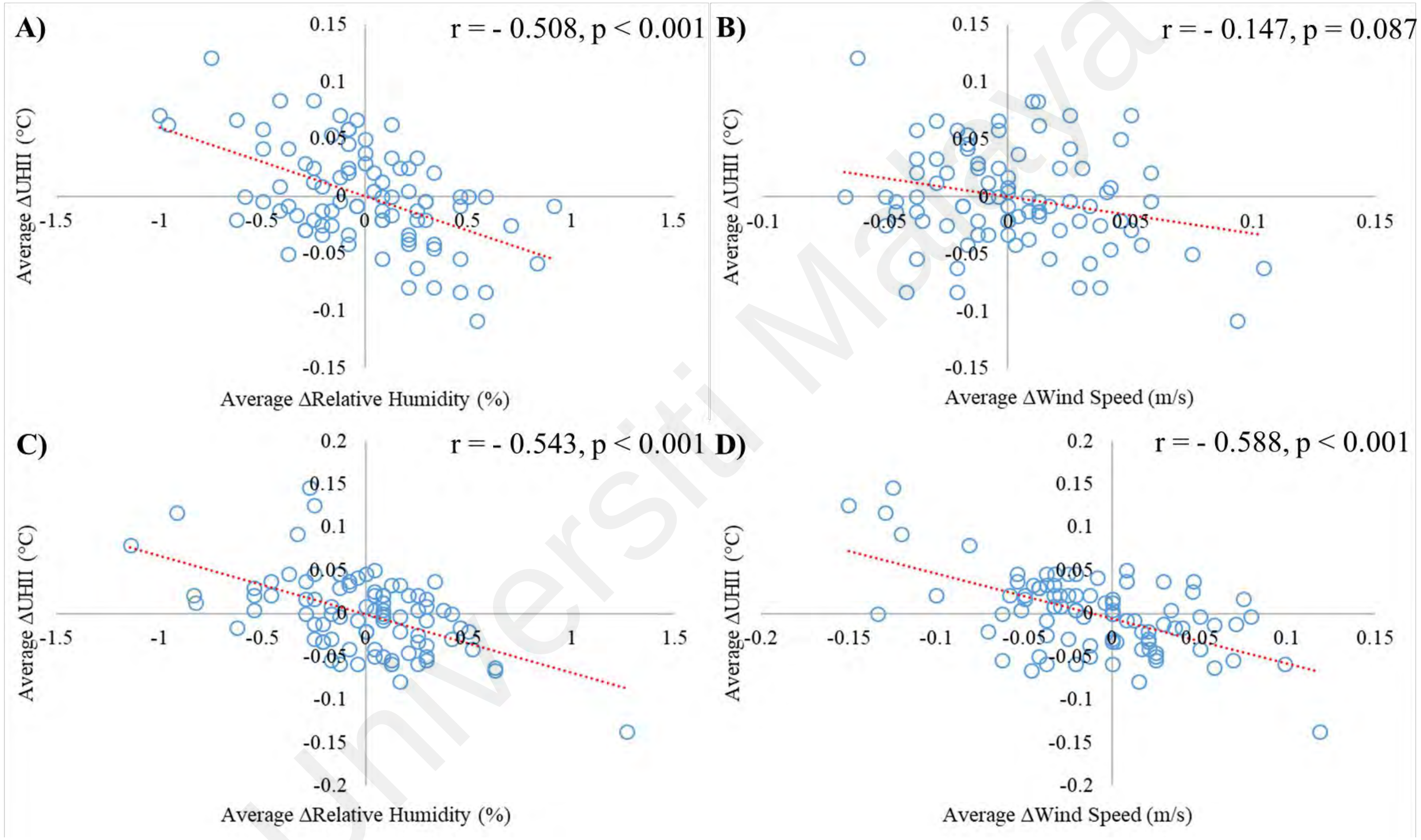


Figure 4.16: Linear regression of △UHII with △relative humidity and △wind speed: (A&B) PJ station; (C&D) SUB station

Table 4.4: Linear regression equations, Coefficient of Determination (R^2) and Pearson correlation (r) between UHII and selected meteorological parameters in PJ and SUB stations

Regression variables	Stations	Regression equations	R^2	r / p-value
UHII, RH, WS	PJ	UHII = -0.052 RH + 4.673	0.323	**-0.568 / p < 0.001***
		UHII = -0.611 WS + 2.036	0.202	**-0.450 / p** < 0.001*
		UHII = -0.051 RH -0.589 WS + 5.377	0.510	**-0.714 / p** < 0.001*
	SUB	UHII = -0.072 RH + 5.916	0.396	**-0.629 / p** < 0.001*
		UHII = -0.715 WS + 2.148	0.361	**-0.601 / p** < 0.001*
		UHII = -0.063 RH -0.096 WS + 5.481	0.397	**-0.630 / p** < 0.001*
△UHII, △RH, △WS	PJ	△UHII = -0.059△RH + 5.315E-0.05	0.258	**-0.508 / p < 0.001***
		△UHII = -0.188 △WS + 0.001	0.022	-0.147 / p = 0.087
		△UHII = -0.064 △RH -0.310 △WS + 0.001	0.315	**-0.562 / p < 0.001***
	SUB	△UHII = -0.068 △RH - 0.001	0.295	**-0.543 / p < 0.001***
		△UHII = -0.525 △WS - 0.006	0.345	**-0.588 / p < 0.001***
		△UHII = -0.050 △RH -0.415 △WS - 0.005	0.490	**-0.700 / p < 0.001***

UHII=Urban Heat Island Intensity; RH=Relative humidity; WS=Wind speed; △(delta)=hourly changes
R^2=Coefficient of Determination
r = Pearson Correlation Coefficient
* refers to the statistical significance at $p < 0.001$

In the PJ station, relative humidity demonstrated a moderate negative linear relationship with UHII ($r = -0.568$, $p < 0.001$), indicating that 0.05 °C of UHII will be decreased for every one unit increase in the average relative humidity (+1 %). Likewise, hourly change in UHII (ΔUHII) and relative humidity (ΔRH) also revealed a moderate negative correlation in the PJ station ($r = -0.508$, $p < 0.001$). Similar findings were reported for the SUB station that illustrated a moderate negative correlation between relative humidity and UHII ($r = -0.629$, $p < 0.001$). A similar moderate negative correlation between hourly change in UHII (ΔUHII) and relative humidity (ΔRH) is observed ($r = -0.543$, $p < 0.001$) in the SUB station. Every 1 % hourly change in relative humidity will contribute to 0.07 °C hourly changes of UHII in the SUB station. The findings of this study are in agreement with the results of the past studies which identified a negative correlation between relative humidity and UHII (Kim and Baik, 2002; Liu et al., 2007; Wong et al., 2016). As clarified by Kim and Baik (2002) and Liu et al. (2007), the evaporation process in drainage-efficient urban surfaces elevates the relative humidity due to an increase in water vapour pressure and a decrease in saturation water vapour pressure. In response to this, the surface air temperature or UHII decreases due to evaporative cooling effects. Thus, the UHII tend to decrease as the relative humidity increases. However, a comparative study by Liu et al. (2009) in a monsoon-influenced humid continental climate zone (Beijing) showed a positive association between relative humidity and temperature during winter due to the use of an urban heating system that exudes water vapour into the air. This accentuates that there is a possibility for a positive association between these variables due to the man-made influences. It is worth mentioning that the influence of relative humidity on weakening the UHII is promulgated as a combined effect of more than one meteorological parameter such as rainfall and cloud cover. High humidity associated with the rainfall events and increased cloud cover tends to block the daytime solar radiation on urban and suburban/rural stations. Lesser solar radiation received by the sites will eventually decrease the nocturnal cooling of the sites and cause little deviations between the temperatures of the urban and suburban/rural stations (He, 2018; Lai et al., 2021).

In terms of wind speed, a low negative correlation ($r = -0.450$, $p < 0.001$) exists between average wind speed and UHII in the PJ station. The resultant regression equation shows that one unit increase (+1 m/s) in the wind speed would decrease UHII by 0.6 °C. However, this effect is insignificant ($r = -0.147$, $p = 0.087$) between hourly change in UHII (ΔUHII) and wind speed (ΔWS) in the PJ station. In the case of the SUB station, it exhibits a moderate negative relationship ($r = -0.601$, $p < 0.001$) between wind speed and UHII. In terms of hourly changes, a moderate negative relationship ($r = -0.588$, $p < 0.001$) is observed with one unit of hourly change (+1 m/s) in wind speed would cause about 0.53 °C hourly changes in UHII. In section 4.3.3, the range of average wind speed in the SUB (1.45 ± 1.04 - 2.20 ± 1.30 m/s) station was reported to be higher than the PJ (1.05 ± 1.09 - 1.35 ± 1.22 m/s) station. In addition, the mean difference of average wind speed as indicated in Table 4.2 is significant between the PJ and SUB stations during the southwest ($Q = 7.530$, $p < 0.001$) and northeast ($Q = 6.225$, $p < 0.05$) monsoon seasons. This adds to the evidence that the high average wind speeds in the SUB station exert a significant influence in lowering the UHII in SUB station via the convective cooling process.

These findings are in agreement with Klysik and Fortuniak, (1999) (Poland), Morris et al. (2001) (Australia), Kim and Baik (2005) (Seoul), Chow and Roth (2006) (Singapore), Memon and Leung (2010) (Hong Kong) and Eastin et al. (2018) (Charlotte) who observed a significant negative correlation between wind speed and UHII in regions of different climate zones. High wind speed is attributed to lessening the temperature variability of the urban stations, thus tends to minimize the magnitudes of UHII by increasing the sensible heat flux loss via convection (He, 2018). High wind speed within the urban stations also results in low magnitudes of UHII by preventing the rural surface based inversions that characterize strong rural cooling (Lai et al., 2021). As reviewed by He (2018), wind speed can significantly reduce or even eliminate the UHI when reaches a certain threshold. Since the spatial distribution of UHI varies with the urban scale that corresponds to the size of the urban population, a higher wind speed threshold is required to mitigate UHI among the larger cities that accommodate a larger population. For example, a wind speed threshold of 3 - 5 m/s is adequate to eliminate the UHI effects in Palo Alto whereas UHI effects in London with a population of 8.5 million can only be eliminated at the wind speed threshold of 12 m/s. In one of the UHI assessments in Melbourne, Morris et al. (2001) revealed that higher cloud cover over certain areas makes the wind speed impose a lesser influence on the magnitudes of Melbourne's UHI. While the influence of other meteorological and urban parameters could be a possible explanation for this relationship, this study has no such data to discuss the contrasting behaviour between UHII and wind speed in the SUB station.

As moderate correlations are obtained between the daily average UHII and the meteorological variables, the combined influences of relative humidity and wind speed on UHII, indicating a strong negative relationship ($r = -0.714$, $p < 0.001$) in the PJ station and a moderate negative relationship ($r = -0.630$, $p < 0.001$) in SUB station. Of worth noting that the correlation coefficients computed for the combined effect of relative humidity and wind speed on UHII in both the PJ and SUB stations are still higher compared to the influence of individual parameters. A similar relationship is recorded for the combined influences of average hourly changes in the relative humidity and wind speed on average hourly changes in UHII. The combined effect of the meteorological variables is moderate ($r = -0.562$, $p < 0.001$) in the PJ station and strong ($r = -0.700$, $p < 0.001$) in the SUB station. This accentuates that the influence of a few meteorological parameters is more pronounced compared to the influence of a single parameter. Therefore, it can be deduced that the high magnitudes of UHII can be expected when the relative humidity and wind speed are relatively low or vice versa, which is consistent with the findings of Huang et al. (2020).

*A version of this chapter has been published as a technical paper in an ISI-indexed, Tier 1 (IF: 7.587 in 2021) journal as: **Ramakreshnan, L.**, Aghamohammadi, N., Fong, C. S., Ghaffarianhoseini, A., Wong, L. P., and Sulaiman, N. M. (2019). Empirical study on temporal variations of canopy-level Urban Heat Island effect in the tropical city of Greater Kuala Lumpur. *Sustainable Cities and Society*, 44, 748-762.

CHAPTER 5 : CONCLUSION

5.1 Introduction

This chapter outlines a comprehensive summary of the main findings of this study to investigate the temporal variations of canopy-level UHII in the selected urban stations of GKL. In order to achieve this, the main findings are presented in three subsections in accordance with the three main objectives of this study such as (i) the temporal analysis of meteorological variables, (ii) the temporal variations of canopy-level UHII and (iii) the association between the selected meteorological variables and UHII in the selected urban and suburban stations in GKL. At the same time, the significance of the study, limitations and recommendations for the future research work based on the gaps in this study is elaborated in the context of GKL.

5.2 Summary of the main findings of this study

The current study is a primary attempt to evaluate temporal variations of canopy-level UHII over seasonal and diurnal scales in the selected urban stations (PJ and SUB) of GKL in reference to a less developed suburban station (SEP). In a broader perspective, observations by a few meteorological stations are inadequate to generalize the local-scale UHI effect experienced by smaller geographical areas to the whole city due to surface heterogeneity, varying urban metabolism and site-specific microclimatic factors. In response to this, a standard experimental protocol for a local-scale urban meteorological investigation (Oke, 2004) is strictly adhered to eliminate any form of biases in the reported findings of this study. Thus, the results of this study anticipated being representative of a local-scale UHI effect experienced within a 500 m radius, from where the meteorological observatories are located in each urban station. Essentially, this study yields some vital findings that answered the existing knowledge gaps on the behaviour of UHI according to temporal variations in the local context of GKL.

5.2.1 Temporal analysis of meteorological variables in the selected urban and suburban stations in GKL

It is noteworthy that authentic UHI assessments should incorporate bigger datasets of meteorological observations collected over a long period. In this study, a complete set of meteorological data from the year 2016 is utilized to analyze the meteorological conditions conducive to the development of UHI in the selected urban stations of GKL. A total of 112 calm and clear days in the selected urban and suburban stations are included in the analysis after excluding days with the synoptic-scale effects caused by the daily accumulated rainfall (>0.1 mm) and days with moderate to strong winds (>6.00 m/s).

Although variations in the average air temperature are significant in the urban and suburban stations, they exhibit almost similar trends in seasonal and diurnal variations. The findings revealed a relatively low (0.59 °C) average air temperature difference between the urban stations, PJ (29.75 °C) and SUB (29.16 °C), thus highlighting that the two urban stations share similar thermal characteristics. On top of that, the average air temperature difference between the PJ-SEP pair is observed to be higher (1.22 °C) than the SUB-SEP pair (0.63 °C). Such temperature deviations justify the reasons for the high UHII recorded in the PJ station compared to the SUB urban station. Besides, maximum temperatures between the ranges of 36.4 - 36.9 °C are recorded during late afternoon hours (2 - 4 pm) in both urban stations corresponding to the vibrant anthropogenic activities and maximum solar radiation in the urban centres. However, the SEP station is reported to be warmer than the urban stations from 9.00 am until 12.00 pm, possibly due to exposure to intense solar radiation on the sparsely built and more open land use structure.

The average relative humidity demonstrated an inverse relationship with the average temperature in the urban and suburban stations. In terms of diurnal variations, average relative humidity showed a gradually decreasing trend with increasing average temperatures after sunrise in all the stations. Even though the maximum relative humidity is reported in the coolest months of December-January in the PJ (96.00%), SUB (97.00%) and SEP (94.00%) stations, the highest average relative humidity in PJ (72.25%), SUB (76.50%) and SEP (79.19%) stations are recorded in May associated with the pre-southwest monsoon. Essentially, high seasonal variability is observed during the northeast monsoon season in all the three stations explicating that the relative humidity data is more dispersed from January to April. On top of that, the highest average relative humidity assemblages are recorded during the pre-southwest, pre-northeast and northeast monsoon seasons, which can be associated with heavy monthly rainfall records in those seasons for all the stations. It should also be noted that the SEP station recorded the highest average relative humidity values throughout the year due to the land use that retains a big portion of natural vegetation in GKL.

On the other hand, there is a distinct seasonal variation in the average wind speed of SUB and SEP stations compared to the PJ station. The range of average wind speed is the highest in SEP (1.54 ± 0.45 to 2.56 ± 0.94 m/s) station, followed by the SUB (1.45 ± 1.04 to 2.20 ± 1.30 m/s) and PJ (1.05 ± 1.09 to 1.35 ± 1.22 m/s) stations. During the northeast monsoon season, PJ, SUB and SEP stations experience 99.30%, 93.80% and 88.50% episodes of calm winds (≤ 4.00 m/s) from the northeast direction, except for the

SUB station (northwest direction). During the southwest monsoon season, the calm wind is predominantly blowing from the southeast direction in all the stations (PJ: 80.30%, SUB: 93.20 %, SEP: 96.10%) at speeds between 0-4.00 m/s. On the diurnal scales, similar periodic behaviour is observed in all the stations. SEP station always records the highest wind speed among the three stations in all the four monsoon seasons, especially before sunrise and after sunset. Apparently, higher wind speed is always observed in SUB station compared to SEP station during the late afternoon before continuing to decrease after the sunset. In brief, the wind speed in all the three stations is relatively calm (0-4.00 m/s) under stable atmospheric conditions in terms of seasonal and diurnal scales.

In conclusion, ANOVA and Tukey's HSD computations revealed a statistically significant difference between the means of the average air temperature, relative humidity and wind speed at the urban and suburban stations. In terms of seasonal variations, a significant difference in the mean of the average temperature, relative humidity and wind speed between the PJ, SUB and SEP stations was observed during the southwest monsoon season. This finding indicates a complex relationship between these parameters. Notably, the difference between the mean of the average temperature of PJ-SEP pair is statistically significant during northeast ($Q = 4.037$, $p < 0.05$) and southwest monsoon ($Q = 11.344$, $p < 0.001$) seasons whereas SUB-SEP pair register statistical significance during southwest monsoon ($Q = 7.742$, $p < 0.001$) only.

5.2.2 Temporal variations of canopy-level UHII in the selected urban station in GKL

Despite prominent variations in the magnitudes of the monthly average UHIIs, both PJ and SUB stations display almost similar seasonal trends in the year 2016. The yearly average of the UHII in the PJ station (1.25 °C) is higher compared to the SUB station (0.67 °C). Both PJ (0.74 - 1.70 °C) and SUB (0.15 - 1.40 °C) stations recorded the highest magnitude of average UHII within the specified ranges during relatively drier months associated with southwest monsoon seasons. Furthermore, the monthly average UHIIs of both PJ (April – August) and SUB (April – September) stations are higher than the yearly average UHII during the pre-southwest and southwest monsoon seasons. This finding elucidates that the development of UHI in both PJ and SUB stations is more apparent during the hot and drier months related to the southwest monsoon season. In both stations, the monthly averages of the UHII are lower than the yearly average UHII during the wet months associated with the northeast monsoon.

In terms of diurnal variations, the daily average of the UHII in the PJ station (1.19 °C) is higher compared to the SUB (0.73 °C) station. Besides, both stations evince variations in the time frame at which the lowest and highest UHIIs are observed in the diurnal scales. In the PJ station, the hourly averages of UHII range from 0.34 °C (11 am) to 1.78 °C (8 p.m.), with the magnitudes surpassing the daily average usually recorded before sunrise (1 a.m. to 7 a.m.) and from late afternoon (3 p.m. onwards) until the midnight (12 a.m.). Contrarily, the hourly UHII exceeding the daily average is usually recorded from 11 a.m. until 10 p.m. in the SUB station. The difference in the hourly average UHII between both PJ and SUB stations is big such as at 0.86°C before sunrise and 1.08 °C after sunset, indicating nocturnal UHI is more pronounced in the PJ station. It is important to note that both PJ and SUB stations registered positive hourly average

UHII in a day, which indicates the average air temperature at urban stations is always higher compared to that of the suburban station.

Of note, the hourly cooling (warming) rate differences between the urban and suburban stations can be used to support these findings. The outcomes outline that the highest cooling rate in the SUB (1.10 °C/h) and PJ (0.90 °C/h) is attained around 6 p.m., indicating that the maximum heating is occurring during the evening time. Furthermore, the cooling rate of the SUB station (0.18 - 1.10 °C/h) is higher than that of the PJ station (0.13 – 0.90 °C/h) from late afternoon to night (3 p.m. - 12 a.m.). It also should be noted that the cooling rate of the SEP station is the lowest before sunrise (0.15 – 0.34 °C/h) and after sunset (0.20 – 0.47 °C/h). In response to this, SEP station tend to release heat faster than PJ and SUB stations, justifying the possible reasons for the development of nocturnal UHI with varying intensities in these urban stations. Besides, the diurnal UHI attains a maximum intensity when rural and urban cooling rates become almost equal in magnitude around one hour after sunset for PJ station and around late afternoon for SUB station.

In terms of distribution of hourly UHII events, most of the hourly UHIIs between 1-3 °C occur at night during all the monsoon seasons. In particular, UHII of more than 3 °C during the hottest and driest southwest monsoon season occur the most (5.52 %) during the nights in PJ station compared to the daytime (4.58 %). In the case of the SUB station, about 9.28% of the UHI events more than 2 °C are attributed to the nighttime compared to the daytime (5.94%). These findings further validate that high UHIIs are more frequent at nights compared to the daytime.

5.2.3 Association between selected meteorological variables and UHII in the urban stations in GKL.

In general, the findings underscore a moderate relationship between relative humidity, wind speed and UHII in the urban stations in GKL. The relative humidity demonstrated a moderate negative linear relationship with UHII in PJ ($r = -0.568$, $p < 0.001$) and SUB ($r = -0.629$, $p < 0.001$) stations. Likewise, hourly change in UHII (ΔUHII) and relative humidity (ΔRH) also revealed a moderate negative correlation in PJ ($r = -0.508$, $p < 0.001$) and SUB ($r = -0.543$, $p < 0.001$) stations. The days with high relative humidity elevate the atmospheric water vapour that would decrease the daytime radiation load at the urban stations. Due to this, radiative cooling differences between the urban and suburban stations are reduced and thus, weakening the nocturnal UHIIs.

Even though, wind speed exerts a low negative correlation with UHII in the PJ ($r = -0.450$, $p < 0.001$) station, the strength of this relationship is moderate in the SUB ($r = -0.601$, $p < 0.001$) station. In terms of hourly changes, a moderate negative relationship ($r = -0.588$, $p < 0.001$) is observed between hourly change in UHII (ΔUHII) and wind speed (ΔWS) in the SUB station. Nonetheless, this effect is insignificant ($r = -0.147$, $p = 0.087$) in the PJ station. The findings outlined that the seasonal variation of the wind in the SUB (1.45 ± 1.04 - 2.20 ± 1.30 m/s) station is higher compared to the PJ (1.05 ± 1.09 - 1.35 ± 1.22 m/s) station in this study. With respect to this, it can be said that the wind speed has a more profound impact on weakening the UHII in the SUB station via an intensified convective cooling.

The combined influences of relative humidity and wind speed on UHII indicate a strong negative relationship ($r = -0.714$, $p < 0.001$) in the PJ station and a moderate negative relationship ($r = -0.630$, $p < 0.001$) in the SUB station. Meanwhile, the combined influences of average hourly changes in the relative humidity and wind speed on △UHII whereby the combined effect of the meteorological variables is moderate ($r = -0.562$, $p < 0.001$) in PJ station and strong ($r = -0.700$, $p < 0.001$) in SUB station.

5.3 Novelty and implications of the study findings

In a nutshell, it can be said that this study provided a detailed description of the temporal variations of UHII in the selected, well-developed and vibrant urban areas of PJ and SUB, which highlights the influence of urbanization on the deterioration of the thermal regime of these urban centres. Despite their functions and roles as vibrant commercial and administrative hubs in the heart of GKL, there is no UHI assessments have been conducted in the city centres of PJ and SUB. Therefore, the UHIIs reported in this study can be considered as the first baseline reported for these two urban centres. Similar to National Urbanization Policy (NUP) 1 and 2 that call for mitigation actions to alleviate the UHI phenomenon in Malaysia (PLANMalaysia, 2006; 2016), the local actions plans by the city councils of PJ and SUB tend to place an emphasis on the UHI mitigation efforts in their urban development agenda before addressing the severity of the phenomena in their cities. The Strategic Plan of Petaling Jaya City Council 2021-2025 and Green City Action Plan by Subang Jaya City Council stress on the implementation of urban greening and riverfront rejuvenation as UHI mitigations (Strategic Planning of Petaling Jaya City Council, 2021; Urbanice Malaysia and MBSJ Voluntary Local Review, 2021). However, the success of these mitigations cannot be tracked without having the baseline of UHII and consistent follow-up assessments in both of these city centres. Therefore, the findings from these studies can be regarded as the fundamental baseline to identify the severity of urban warming in PJ and SUB for the articulation of heat adaptation or mitigation strategies as well as to test the effectiveness of such strategies in the tropics. This is essential to materialize the aspiration of GKL to be among the global top-20 most liveable cities with high quality of living as indicated within the Economic Transformation Programme (Economic Planning Unit (EPU), 2010). It is also worth mentioning that there are no updates on UHII compared to the one reported in the current study in both of these stations by the time this thesis draft is being written and revised prior to submission. Hence, the UHIIs reported in this study are still relevant as a reference and can be used by the city councils and researchers to devise follow-up studies and heat interventions.

Another important implication of the study is the improved reliability of the canopy-level UHII quantified based on the observed air temperature within the urban canopy layer, sensed at human height levels in the PJ and SUB stations. Most of the UHI studies that have been conducted in various regions of GKL in the past have utilized satellite-based LST measurements that defined UHI in the form of SUHI. This is mainly due to the distinct advantages of LST over ground measurements in terms of good spatial coverage, which has been a major criticism of the canopy-level UHI literature (Stewart, 2011). In comparison with the in-situ measurements, the use of satellite datasets was reported to lead to the over-estimation of UHII due to the upward bias of satellite-based measurements caused by the synoptic conditions (Venter et al., 2021). In addition, the studies that have compared the canopy-level UHI with SUHI suggested that they might have different diurnal and seasonal trends (Ho et al., 2016; Wang et al., 2017). In regards to this, despite limited spatial coverage, the ground measurements are still valid to provide reliable UHI quantification. To the best of the knowledge of the student author, the present study serves as one of the starting points to evaluate the status of canopy-level UHII based on ground measurements at human height in PJ and SUB stations in GKL.

Besides, the findings are essential to serving as baseline data to identify the severity of the urban warming effect in major cities of Malaysia such as PJ and SUB for the articulation of heat adaptation or mitigation strategies in tandem with the Malaysia's pledge made in the Paris Summit 2015. This is also crucial to materialize Malaysia's commitment made in the 26th Conference of Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC), targeting actions to accelerate the country's action toward the goal of keeping the global temperature rise in this century to 2 °C above pre-industrial levels. Compared to the surface UHI, the canopy-level UHII sensed at the human height levels is also crucial to evaluating the heat-related physical and psychosocial impacts including thermal discomfort and heat stress among the urbanites (Ho et al., 2016; Peng et al., 2022; Venter et al., 2021) who are living in the PJ and SUB stations.

Besides, this study in PJ and SUB stations are holistic and the reported UHIIs for both of these stations are reliable as document the temporal variations of canopy-level UHII by examining (i) the temporal variations of the meteorological parameters between the stations, (ii) temporal variations of UHII, (iii) diurnal warming rates of the stations and finally deducing (iv) the association between the selected meteorological parameters and UHII in stages. Indeed, a holistic understanding of the temporal variability of canopy-level UHII and its association with the environmental parameters is needed to ensure effective and coherent development of adaptation strategies aimed at the improvement of the urban thermal environment. Besides, this study adds more evidence on the influence of meteorological parameters on canopy-level UHII in the tropical context of Malaysia. Hence, the findings reported in this study are expected to fill the existing knowledge gap and climate literacy on how strongly the meteorological factors can affect the UHII in an equatorial country like Malaysia by adding more research evidence from the tropical region. The findings accelerate an in-depth understanding of the potential use of synoptic conditions and meteorology characteristic-based UHI mitigation strategies in the local context. The acquired knowledge is expected to assist the urban planners and designers to develop climate-friendly city designs that allow a proper wind flow and evaporative cooling effects to improve the urban thermal environment. Unlike the conventional use of 'urban' and 'rural' (reference site) site classification, this study characterized the study sites as 'urban' and 'suburban' to fit the vernacular GKL landscapes. As a reference site that fit the definition of 'rural' is hardly discovered together with the availability of Automated Principal Weather Stations, this study adopted the SEP as a reference site that portrays different degrees of development and growth compared to the PJ and SUB stations.

As wind speed and relative humidity impose a significant influence on reducing the UHII of the urban stations, it should be noted that only cooler wind sources could mitigate UHI effects whereas warm wind sources will exacerbate UHI effects (He et al., 2017). Therefore, urban ventilation corridors can be constructed along the prevailing winds generated from cold sources such as riverside, rural and suburban areas in both PJ and SUB stations. Indeed, urban ventilation corridors can be established through connections of urban open areas such as major roads, open spaces, green lands and low-rise buildings (Liu and Chen, 2010). High-rise and tall buildings that block the prevailing wind can be re-shaped to improve the ventilation efficiency in these urban stations (Mou et al., 2017). Moreover, the underlying surface of urban ventilation corridors can be paved with cool materials, grasslands and water bodies to elevate the humidity of the air in the introduced wind. For cities that are controlled by the heated prevailing wind, green barriers such as trees and forests should be set at the windward of the city to block the hot wind (He et al., 2017). Meanwhile, the local cold sources are required for the establishment of a local ventilation corridor for UHI mitigation. On another hand, urban greenery should be concerned to increase the relative humidity in the air via vegetation transpiration. In addition, excessive heat in urban areas should be ejected through urban ventilation corridors to weaken the significance of excessive heat in the urban stations.

5.4 Limitations of the study

Despite providing an important contribution to urban climate and UHI literacy in the context of GKL, this study is subjected to a number of inherent limitations of empirical investigations that warrant a careful consideration when interpreting its findings. Firstly, the annual and inter-annual variability of canopy-level UHII in PJ and SUB stations that communicates a long-term representation of urbanization-induced detriments of local climate is not presented in this study due to data acquisition difficulties during the study commencement period. The analysis of UHII based on large datasets spanning over several years is indispensable to visualize the incidence of any periodical behaviour of UHII on yearly basis. Such observation adds additional valid evidence to the seasonal dynamics of UHII observed in this study. Even though this study utilizes one year of datasets to examine the temporal variations of canopy-level UHII in PJ and SUB stations, the reliability of the UHII computations is increased by analyzing its average hourly and daily variations for all the 112 days as reported in this study. On top of that, a careful data cleaning and management is undertaken to ensure that the analyzed datasets for the year 2016 are free from any form of synoptic influences caused by the rainfall and wind speed in the urban and suburban stations that could cause under- or over-estimation of the UHII for both PJ and SUB stations.

It is worth mentioning that the reliability of the meteorological criteria influencing UHI development can be increased by incorporating a large number of meteorological observatories during the analysis. As the setting (topography, altitude, types and height of the instruments) of the meteorological observatories is pivotal to minimizing deviations in the measurements between the stations, this study only used datasets collected from the standard Automated Principal Weather Stations (APWS) of MetMalaysia. These stations accommodate a comprehensive set of primary instruments and sensors for collecting the weather data at the human height level. In addition, the design of APWS follows the standards set by the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO) to fulfil international requirements for weather and climate monitoring. Notwithstanding this, only three APWS are available in GKL as documented in this study. Due to this, the present study did not provide any spatial variations of UHII due to the limitations of in-situ measurements by standard meteorological observatories.

Furthermore, the three-dimensional urban morphology such as volumetric density and sky-view factors around the meteorological observatories that may exert a notable influence on local UHII (Stewart and Oke, 2012) is not quantitatively associated with the temporal variations of the UHII due to the lack of such data in this study. Besides, studying UHI from a three-dimensional perspective is also crucial to understanding its mesoscale variations in both horizontal and vertical positions (Kim and Brown, 2021). Moreover, such data is excluded as the objectives of this study is focused on the evaluation of the relationship between the meteorological parameters and UHII of the urban stations. However, a description of the study areas including the height of the buildings, anthropogenic activities and common land cover materials (paved with asphalt and tar, bricks, glass facades, etc.) is provided for the urban stations. The PJ, SUB and

SEP stations are also described in terms of LCZ classifications by highlighting the attributes of the respective stations as tabulated in Table 3.1. It is also worth mentioning that little morphological variations and no anomalous obstacles such as trees or buildings are observed within a radius of 500 m in the surrounding landscape of the meteorological observatories that impose little influence on the meteorological data. Such conditions enable the observatories to generate data that represents the local-scale microclimate of that particular land use.

This study mainly evaluated the single and combined influences of relative humidity and wind speed on UHII in PJ and SUB stations as the existing literature expounded that the role of these meteorological parameters is more significant on the magnitude of UHI in the tropical context. However, data such as cloud cover and solar radiation that could produce a significant impact on the UHII of these stations is not incorporated due to the absence of such data in the meteorological observatories of PJ and SUB stations. As this study did not include the three-dimensional design of the urban station, it only analyzed the plausible relationship between wind speed and UHII without analyzing the impact of wind direction and its sources. Nonetheless, a comprehensive analysis of wind speed, direction and sources adds more evidence on its role as a mitigation of UHI impact in the urban stations.

5.5 Recommendations for future research

While presenting crucial findings on the temporal variations of canopy-level UHII in the selected urban stations of GKL, the existing limitations of the present study can be anticipated as the gaps to facilitate future research directions on this topic. In response to the limitation related to the lacking of several years of dataset, future studies should deploy datasets of a few years to examine the annual and inter-annual variability of canopy-level UHII in PJ and SUB stations to elucidate a more comprehensive interpretation of urbanization-induced UHI impacts. Such analysis adds more evidence to verify the seasonal and diurnal variations of UHII in PJ ad SUB stations to check on the incidence or repetition of similar temporal patterns in all the years included in the analysis.

Secondly, future studies should include the meteorological datasets obtained from a large network of meteorological observatories in GKL. With this, the UHI analysis can be even extended to cover more urban stations located in the heart of GKL with different degrees of urbanization and metabolism. The incorporation of more urban stations and meteorological observatories in the UHI analysis increases the spatial coverage of UHII and enables the researchers to compute an average UHII that can be associated with the whole region of GKL. Such information enables the future researchers to monitor the annual fluctuations of the average UHII in GKL over the years. Despite enabling the traction of the UHI influence on the local climate and global warming, such data can be easily associated with the urbanization rate of GKL over the years.

Thirdly, as limited standardized APWS of MetMalaysia is available in GKL, future studies may employ some innovative approaches to the current methodology to produce comprehensive results of the local UHI phenomenon. Integration of mobile weather trackers, drones and unmanned aerial vehicles with meteorological network observations could produce a more holistic approach to cover an extended geographical area and vertical profile of UHII in the urban stations of GKL. However, the practicality of integrating these approaches in the field to generate an authentic UHII in GKL needs to be studied in advance before employing such techniques on the ground.

Fourthly, it is apparent that the seasonality of meteorological variables and the three-dimensional properties of a city have complex effects on UHII. Thus, future studies can incorporate more urban variables such as sky-view factor, volumetric density, albedo and the others to evaluate their influence on UHII. Besides, the incorporation of more explanatory variables of UHI from both meteorological and urban factors is a requisite to identify their pivotal association with UHI intensification in the tropical context. With such acquired knowledge of the UHI issue and related underlying mechanisms, urban planners, designers and decision makers can perform more evidence-based decision making to create, reform or rejuvenate climate-friendly sustainable cities for enhanced liveability in future.

REFERENCES

Acero, J. A., Arrizabalaga, J., Kupski, S., and Katzschner, L. (2013). Urban heat island in a coastal urban area in northern Spain. *Theoretical and Applied Climatology, 113*(1-2), 137-154. doi: 10.1007/s00704-012-0774-z

Adilah-Amrannudin, N., Hamsidi, M., Ismail, N. A., Ismail, R., Dom, N. C., Ahmad, A. H., ... and Camalxaman, S. N. (2016). Genetic polymorphism of Aedes albopictus population inferred from ND5 gene variabilities in Subang Jaya, Malaysia. *Journal of the American Mosquito Control Association*, 32(4), 265-272. doi: 10.2987/16-6579.1

Aflaki, A., Mirnezhad, M., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Omrany, H., Wang, Z. H., and Akbari, H. (2016). Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong. *Cities, 62*, 131-145. doi: 10.1016/j.cities.2016.09.003

Aflaki, A., Mirnezhad, M., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Omrany, H., Wang, Z. H., and Akbari, H. (2017). Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong. *Cities, 62*, 131-145. doi: 10.1016/j.cities.2016.09.003

Aghamohammadi, N., Ramakreshnan, L., Fong, C. S., and Sulaiman, N. M. (2021). Urban Heat Island, contributing factors, public responses and mitigation approaches in the tropical context of Malaysia. In Urban Heat Island (UHI) Mitigation (pp. 107-121). Springer, Singapore.

Ahmed, A. Q., Ossen, D. R., Jamei, E., Abd Manaf, N., Said, I., and Ahmad, M. H. (2015). Urban surface temperature behaviour and heat island effect in a tropical planned city. *Theoretical and Applied Climatology, 119*(3-4), 493-514. doi: 10.1007/s00704-014-1122-2

Akasah, Z. A., and Doraisamy, S. V. (2014). 2014 Malaysia flood, impacts & factors contributing towards the restoration of damages. *Journal of Scientific Research and Development, 2*(14), 53-59.

Alexander, P., and Mills, G. (2014). Local Climate Classification and Dublin's Urban Heat Island. *Atmosphere, 5*(4), 755-774. doi: 10.3390/atmos5040755

Amanollahi, J., Tzanis, C., Ramli, M. F., and Abdullah, A. M. (2016). Urban heat evolution in a tropical area utilizing Landsat imagery. *Atmospheric Research, 167*, 175-182. doi: 10.1016/j.atmosres.2015.07.019

Amorim, M. C. D. C. T., and Dubreuil, V. (2017). Intensity of Urban Heat Islands in Tropical and Temperate Climates. *Climate Research, 5*(4), 91. doi: 10.3390/cli5040091

Amorim, M. C. D. C. T. (2020). Daily evolution of urban heat islands in a Brazilian tropical continental climate during dry and rainy periods. *Urban Climate*, 34, 100715. doi: 10.1016/j.uclim.2020.100715

Arifwidodo, S. D., and Tanaka, T. (2015). The characteristics of urban heat island in Bangkok, Thailand. *Procedia-Social and Behavioral Sciences*, 195, 423-428. doi: 10.1016/j.sbspro.2015.06.484

Arnds, D., Böhner, J., and Bechtel, B. (2017). Spatio-temporal variance and meteorological drivers of the urban heat island in a European city. *Theoretical and applied climatology*, 128(1-2), 43-61. doi: 10.1007/s00704-015-1687-4

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology, 23*(1), 1-26. doi: 10.1002/joc.859

Bartesaghi-Koc, C., Osmond, P., and Peters, A. (2022). Innovative use of spatial regression models to predict the effects of green infrastructure on land surface temperatures. *Energy and Buildings*, 254, 111564. doi: 10.1016/j.enbuild.2021.111564

Bejaran, R. A., and Camilloni, I. A. (2003). Objective method for classifying air masses: an application to the analysis of Buenos Aires' (Argentina) urban heat island intensity. *Theoretical and Applied Climatology, 74*(1-2), 93-103. doi: 10.1007/s00704-002-0714-4

Benrazavi, R. S., Binti Dola, K., Ujang, N., and Sadat Benrazavi, N. (2016). Effect of pavement materials on surface temperatures in tropical environment. *Sustainable Cities and Society, 22*, 94-103. doi: 10.1016/j.scs.2016.01.011

Buyadi, S. N. A., Mohd, W. M. N. W., and Misni, A. (2013a). Green Spaces Growth Impact on the Urban Microclimate. *Procedia - Social and Behavioral Sciences, 105*, 547-557. doi: 10.1016/j.sbspro.2013.11.058

Buyadi, S. N. A., Mohd, W. M. N. W., and Misni, A. (2013b). Impact of Land Use Changes on the Surface Temperature Distribution of Area Surrounding the National Botanic Garden, Shah Alam. *Procedia - Social and Behavioral Sciences, 101*, 516-525. doi: 10.1016/j.sbspro.2013.07.225

Buyadi, S. N. A., Mohd, W. M. N. W., and Misni, A. (2014). Quantifying green space cooling effects on the urban microclimate using Remote Sensing and GIS techniques. *In FIG Congress 2014 Engaging the Challenges – Enhancing the Relevance, Kuala Lumpur, Malaysia, 16-21 June 2014.*

Camilloni, I., and Barrucand, M. (2012). Temporal variability of the Buenos Aires, Argentina, urban heat island. *Theoretical and Applied Climatology, 107*(1-2), 47-58. doi: 10.1007/s00704-011-0459-z

Chakraborty, T., Sarangi, C., and Tripathi, S. N. (2017). Understanding diurnality and inter-seasonality of a sub-tropical urban heat island. *Boundary-Layer Meteorology*, 163(2), 287-309. doi: 10.1007/s10546-016-0223-0

Che-Ani, A. I., Shahmohamadi, P., Sairi, A., Mohd-Nor, M. F. I., Zain, M. F. M., and Surat, M. (2009). Mitigating the urban heat island effect, some points without altering existing city planning. *European Journal of Scientific Research, 35*(2), 204-216.

Chew, L. W., Liu, X., Li, X. X., and Norford, L. K. (2021). Interaction between heat wave and urban heat island: A case study in a tropical coastal city, Singapore. *Atmospheric Research*, 247, 105134. doi: 10.1016/j.atmosres.2020.105134

Chow, W. T. L., and Roth, M. (2006). Temporal dynamics of the urban heat island of Singapore. *International Journal of Climatology, 26*(15), 2243-2260. doi: 10.1002/joc.1364

Chuen, O. C., Karim, M. R., and Yusoff, S. (2014). Mode choice between private and public transport in Klang Valley, Malaysia. *The Scientific World Journal*. 2014. doi: 10.1155/2014/394587

Cuadrat, J. M., Serrano-Notivoli, R., Barrao, S., Saz, M. Á., and Tejedor, E. (2022). Temporal variability of the urban heat island in Zaragoza (Spain). *Cuadernos de Investigación Geográfica*, 48(1), 97-110. doi: 10.18172/cig.5022

Davis, M. P., Nordin, N. A., Ghazali, M., Durak, M. J., and Reimann, G. (2005). Reducing Urban Heat Island effect with thermal comfort housing and Honeycomb Townships. *In Conference on Sustainable Building South East Asia , Malaysia, 11-13 April 2005.*

de Souza, D. O., and dos Santos Alvalá, R. C. (2014). Observational evidence of the urban heat island of Manaus City, Brazil. *Meteorological Applications*, 21(2), 186-193. doi: 10.1002/met.1340

Dou, J., Wang, Y., Bornstein, R., and Miao, S. (2015). Observed spatial characteristics of Beijing urban climate impacts on summer thunderstorms. *Journal of Applied Meteorology and Climatology*, 54(1), 94-105. doi: 10.1175/JAMC-D-13-0355.1

Dziauddin, M. F. (2019). Estimating land value uplift around light rail transit stations in Greater Kuala Lumpur: An empirical study based on geographically weighted regression (GWR). *Research in Transportation Economics*, 74, 10-20.

Eastin, M. D., Baber, M., Boucher, A., Di Bari, S., Hubler, R., Stimac-Spalding, B., and Winesett, T. (2018). Temporal variability of the Charlotte (sub) urban heat island. *Journal of Applied Meteorology and Climatology*, 57(1), 81-102. doi: 10.1175/JAMC-D-17-0099.1

Economic Planning Unit (EPU) (2010). Tenth Malaysia Plan 2011-2015. Retrieved from https://www.pmo.gov.my/dokumenattached/RMK/RMK10_Eds.pdf.

Economic Planning Unit (EPU) (2016). Eleventh Malaysia Plan 2016-2020. Retrieved from https://www.pmo.gov.my/dokumenattached/speech/files/RMK11_Speech.pdf

Economic Transformation Programme (ETP) (2014). Annual Report 2014. Retrieved from https://www.pemandu.gov.my/assets/publications/annual-reports/ETP_2014_EN.pdf

Ellefsen, R. (1991). Mapping and measuring buildings in the canopy boundary layer in ten US cities. *Energy and Buildings, 16*(3-4), 1025-1049. doi: 10.1016/0378-7788(91)90097-M

Elsayed, I. S. (2012a). The effects of traffic activity on the intensity of the Urban Heat Island, A case study on the city of Kuala Lumpur, Malaysia. *Sudan Engineering Society Journal, 58*(2), 9-16.

Elsayed, I. S. (2012b). A study on the urban heat island of the city of Kuala Lumpur, Malaysia. *Journal of King Abdulaziz University, 23*(2), 121. doi: 10.4197/Met.23-2.8

Emmanuel, R., and Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK. *Landscape and Urban Planning, 138*, 71-86. doi: 10.1016/j.landurbplan.2015.02.012

Environmental Protection Agency (EPA) (2009). Environmental Protection Agency (EPA) (2009). Urban Heat Island basics. Reducing Urban Heat Islands, Compendium of Strategies; Chapter 1; Draft Report. Retrieved from http://www.epa.gov/heatisland/resources/compendium.htm.

Ezber, Y., Lutfi Sen, O., Kindap, T., and Karaca, M. (2007). Climatic effects of urbanization in Istanbul: a statistical and modeling analysis. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 27*(5), 667-679. doi: 10.1002/joc.1420

Feng, J. L., Cai, X. M., and Chapman, L. (2021). A tale of two cities: The influence of urban meteorological network design on the nocturnal surface versus canopy heat island relationship in Oklahoma City, OK, and Birmingham, UK. *International Journal of Climatology*, 41, E445-E462. doi: 10.1002/joc.6697

Firozjaei, M. K., Weng, Q., Zhao, C., Kiavarz, M., Lu, L., and Alavipanah, S. K. (2020). Surface anthropogenic heat islands in six megacities: An assessment based on a triple-source surface energy balance model. *Remote Sensing of Environment*, 242, 111751. doi: 10.1016/j.rse.2020.111751

Fortuniak, K., Kłysik, K., and Wibig, J. (2006). Urban–rural contrasts of meteorological parameters in Łódź. *Theoretical and applied climatology*, 84(1), 91-101. doi: 10.1007/s00704-005-0147-y

Gago, E. J., Roldan, J., Pacheco-Torres, R., and Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews, 25*, 749-758. doi: 10.1016/j.rser.2013.05.057

Gasim, M. B., Toriman, M. E., and Abdullahi, M. G. (2014). Floods in Malaysia, Historical Reviews, Causes, Effects and Mitigations Approach. *International Journal of Interdisciplinary Research and Innovations, 2*(4), 59-65.

Giridharan, R., and Emmanuel, R. (2018). The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. *Sustainable cities and society*, 40, 677-687. doi: 10.1016/j.scs.2018.01.024

Grimmond, C. S. B., and Oke, T. R. (1991). An evapotranspiration‐interception model for urban areas. *Water Resources Research, 27*(7), 1739-1755. doi: 10.1029/91WR00557

Govind, N. R., and Ramesh, H. (2019). The impact of spatiotemporal patterns of land use land cover and land surface temperature on an urban cool island: a case study of Bengaluru. *Environmental monitoring and assessment,* 191(5), 1-20. doi: 10.1007/s10661-019-7440-1

Harun, Z., Reda, E., Abdulrazzaq, A., Abbas, A. A., Yusup, Y., and Zaki, S. A. (2020). Urban heat island in the modern tropical Kuala Lumpur: Comparative weight of the different parameters. *Alexandria Engineering Journal*, 59(6), 4475-4489. doi: 10.1016/j.aej.2020.07.053

Hashim, N., Ahmad, A., and Abdullah, M. (2007). Mapping Urban Heat Island phenomenon, Remote sensing approach. *Journal-The Institution of Engineers, Malaysia, 68*(3), 25-30.

He, B. J. (2018). Potentials of meteorological characteristics and synoptic conditions to mitigate urban heat island effects. *Urban climate*, 24, 26-33. doi: 10.1016/j.uclim.2018.01.004

He, B. J., Wang, J., Liu, H., and Ulpiani, G. (2021). Localized synergies between heat waves and urban heat islands: Implications on human thermal comfort and urban heat management. *Environmental Research*, 193, 110584. doi: 10.1016/j.envres.2020.110584

Ho, H. C., Knudby, A., Xu, Y., Hodul, M., and Aminipouri, M. (2016). A comparison of urban heat islands mapped using skin temperature, air temperature, and apparent temperature (Humidex), for the greater Vancouver area. *Science of the Total Environment*, 544, 929-938. doi: 10.1016/j.scitotenv.2015.12.021

Huang, Q., Li, L., Lu, Y., Yang, Y., and Li, M. (2020). The roles of meteorological parameters in Shanghai's nocturnal urban heat island from 1979 to 2013. *Theoretical and Applied Climatology*, 141(1), 285-297. doi: 10.1007/s00704-020-03214-3

Intergovernmental Panel of Climate Chaange (IPCC) (2007). Climate change 2007: the physical science basis. In Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller HL (eds). Cambridge University Press: New York, 1056.

Ishak, A., Hassan, Z. N. C., Edros, N. H., Zamberi, M. H., and Rahman, M. N. A. (2011). The effect of local climate on Urban Heat Island trend; A case study in urban areas of Ipoh and Kuantan. *Malaysian Meteorological Department (MMD). Ministry of Science, Technology and Innovation, Kuala Lumpur, Malaysia.*

Ivajnsic, D., Kaligaric, M., and Ziberna, I. (2014). Geographically weighted regression of the urban heat island of a small city. *Applied Geography, 53*, 341-353. doi: 10.1016/j.apgeog.2014.07.001

Jamhari, A. A., Sahani, M., Latif, M. T., Chan, K. M., Tan, H. S., Khan, M. F., and Tahir, N. M. (2014). Concentration and source identification of polycyclic aromatic hydrocarbons (PAHs) in PM10 of urban, industrial and semi-urban areas in Malaysia. *Atmospheric Environment*, 86, 16-27. doi: 10.1016/j.atmosenv.2013.12.019

Jarraud, M. (2008). Guide to meteorological instruments and methods of observation (WMO-No. 8). *World Meteorological Organisation: Geneva, Switzerland*.

Jauregui, E. (1986). The urban climate of Mexico City. Urban climatology and its applications with special regard to tropical areas, world climate programme, (WMO-No. 652). Geneva: World Meteorological Organisation. 63-86.

Jochner, S., Alves‐Eigenheer, M., Menzel, A., and Morellato, L. P. C. (2013). Using phenology to assess urban heat islands in tropical and temperate regions. *International journal of climatology*, 33(15), 3141-3151. doi: 10.1002/joc.3651

Kang, S., Lee, D., Park, J., and Jung, J. (2022). Exploring Urban Forms Vulnerable to Urban Heat Islands: A Multiscale Analysis. *Sustainability*, 14(6), 3603. doi: 10.3390/su14063603

Karam, H. A., Pereira Filho, A. J., Masson, V., Noilhan, J., and Marques Filho, E. P. (2010). Formulation of a tropical town energy budget (t-TEB) scheme. *Theoretical and Applied Climatology, 101*(1-2), 109-120. doi: 10.1007/s00704-009-0206-x

Kemarau, R. A., and Eboy, O. V. (2021). The influence of El Niño Southern Oscillation on urban heat island formation at tropical city: Case of Kuching City, Sarawak. *GEOGRAFIA. Malaysian Journal of Society and Space*, 17(4), 288-304.

Kim, Y. H., and Baik, J. J. (2002). Maximum urban heat island intensity in Seoul. *Journal of Applied Meteorology, 41*(6), 651-659. doi: 10.1175/1520-0450(2002)041<0651:muhiii>2.0.co;2

Kim, Y. H., and Baik, J. J. (2005). Spatial and temporal structure of the urban heat island in Seoul. *Journal of Applied Meteorology, 44*(5), 591-605. doi: 10.1175/jam2226.1

Kim, S. W., and Brown, R. D. (2021). Urban heat island (UHI) variations within a city boundary: A systematic literature review. *Renewable and Sustainable Energy Reviews*, 148, 111256. doi: 10.1016/j.rser.2021.111256

Klysik, K., and Fortuniak, K. (1999). Temporal and spatial characteristics of the urban heat island of Lodz, Poland. *Atmospheric Environment, 33*(24-25), 3885-3895. doi: 10.1016/S1352-2310(99)00131-4

Kolokotroni, M., and Giridharan, R. (2008). Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy, 82*(11), 986-998. doi: 10.1016/j.solener.2008.05.004

Kotharkar, R., Bagade, A., and Ramesh, A. (2019). Assessing urban drivers of canopy layer urban heat island: A numerical modeling approach. *Landscape and Urban Planning*, 190, 103586. doi: 10.1016/j.landurbplan.2019.05.017

Kuala Lumpur cuty Hall (KLCH) (2016). Kuala lumpur low carbon society blue print-inception report Kuala Lumpur, Malaysia: KLCH (Kuala Lumpur City Hall).

Kwan, S. C., Tainio, M., Woodcock, J., Sutan, R., and Hashim, J. H. (2017). The carbon savings and health co-benefits from the introduction of mass rapid transit system in Greater Kuala Lumpur, Malaysia. *Journal of Transport & Health*, 6, 187-200. doi: 10.1016/j.jth.2017.06.006

Lai, J., Zhan, W., Voogt, J., Quan, J., Huang, F., Zhou, J., ... and Lee, X. (2021). Meteorological controls on daily variations of nighttime surface urban heat islands. *Remote Sensing of Environment*, 253, 112198. doi: 10.1016/j.rse.2020.112198

Landsberg, J. J., Sands, P. J., Landsberg, J., and Sands, P. (2011). Physiological ecology of forest production: principles, processes and models (Vol. 4). London: Elsevier/Academic Press.

Latif, Z. A., and Kamsan, M. E. S. (2017). Assessing the relationship of land use land cover on surface temperature in city of Shah Alam, Malaysia using LANDSAT-8 OLI. *Journal of Fundamental and Applied Sciences*, 9(5S), 514-525. doi: 10.4314/jfas.v9i5s.36

Lee, S. H., and Baik, J. J. (2010). Statistical and dynamical characteristics of the urban heat island intensity in Seoul. *Theoretical and Applied Climatology*, 100(1), 227-237. doi: 10.1007/s00704-009-0247-1

Leslie-Mazwi, T., Chandra, R. V., Baxter, B. W., Arthur, A. S., Hussain, M. S., Singh, I. P., ... and Hirsch, J. A. (2018). ELVO: an operational definition. *Journal of neurointerventional surgery*, 10(6), 507-509. doi: 10.1136/neurintsurg-2018-013792

Li, L. G., Liang, Z. B., Wang, H. B., Li, C. J., Wang, X. Y., and Zhao, X. L. (2011). Urban heat island characteristics in Shenyang under different weather conditions. *Transactions of Atmospheric Sciences, 34* (1), 66-73

Li, H., Sodoudi, S., Liu, J., and Tao, W. (2020). Temporal variation of urban aerosol pollution island and its relationship with urban heat island. *Atmospheric Research,* 241, 104957. doi: 10.1016/j.atmosres.2020.104957

Li, H., Zhou, Y., Jia, G., Zhao, K., and Dong, J. (2022). Quantifying the response of surface urban heat island to urbanization using the annual temperature cycle model. *Geoscience Frontiers*, 13(1), 101141. doi: 10.1016/j.gsf.2021.101141

Ling, O. H. L., Musthafa, S. N. A. M., and Rasam, A. R. A. (2014). Urban environmental Health: respiratory infection and urban factors in urban growth corridor of Petaling Jaya, Shah Alam and Klang, Malaysia. *Sains Malaysiana*, 43, 1405-1414.

Liu, W., Ji, C., Zhong, J., Jiang, X., and Zheng, Z. (2007). Temporal characteristics of the Beijing urban heat island. *Theoretical and Applied Climatology, 87*(1-4), 213-221. doi: 10.1007/s00704-005-0192-6

Liu, W., You, H., and Dou, J. (2009). Urban-rural humidity and temperature differences in the Beijing area. *Theoretical and Applied Climatology, 96*(3-4), 201–207. doi: 10.1007/s00704-008-0024-6#

Liu, S. Y., and Chen, J. H. (2010). Urban ventilation channel planning method based on local circulation: a case study of Stuttgart, Germany. *Journal of Zhejiang University (Engineering Science)*, 44(10), 1985-1991. doi: 10.3785/j.issn.1008-973X.2010.10.024

Liu, J., & Niyogi, D. (2019). Meta-analysis of urbanization impact on rainfall modification. *Scientific reports*, 9(1), 1-14. doi: 10.1038/s41598-019-42494-2

Mahadi, Z., Mohamad, R. J., and Sino, H. (2017). Public Development Sustainability Values: A Case Study in Sepang Malaysia (Menilai Ciri Kelestarian Nilai Pembangunan Masyarakat di Malaysia: Satu Kajian Kes di Sepang Malaysia). *Akademika*, 87(2). 31-44. doi: 10.17576/akad-2017-8702-03

Makokha, G. L., and Shisanya, C. A. (2010). Temperature cooling and warming rates in three different built environments within Nairobi City, Kenya. *Advances in Meteorology*, 2010. doi: 10.1155/2010/686214

Manteghi, G., Lamit, H., Remaz, D., and Aflaki, A. (2016). Envi-Met Simulation On Cooling Effect Of Melaka River. *International Journal of Energy and Environmental Research, 4*(2), 7-15.

Mathew, A., Sreekumar, S., Khandelwal, S., Kaul, N., and Kumar, R. (2016). Prediction of surface temperatures for the assessment of urban heat island effect over Ahmedabad city using linear time series model. *Energy and Buildings, 128*, 605-616. doi: 10.1016/j.enbuild.2016.07.004

Memon, R. A., and Leung, D. Y. (2010). Impacts of environmental factors on urban heating. *Journal of Environmental Sciences, 22*(12), 1903-1909. doi: 10.1016/S1001-0742(09)60337-5

Memon, R. A., Leung, D. Y. C., Liu, C. H., and Leung, M. K. H. (2011). Urban heat island and its effect on the cooling and heating demands in urban and suburban areas of Hong Kong. *Theoretical and Applied Climatology, 103*(3-4), 441-450. doi: 10.1007/s00704-010-0310-y

Mendonca, F. (2009). Urban heat and urban cool islands: Influences of vegetation and soil surface in some cities, southern Brazil. *In The seventh International Conference on Urban Climate, Yokohama, Japan, 29 Jun-3 July 2009.*

Meng, Q., Hu, D., Zhang, Y., Chen, X., Zhang, L., and Wang, Z. (2022). Do industrial parks generate intra-heat island effects in cities? New evidence, quantitative methods, and contributing factors from a spatiotemporal analysis of top steel plants in China. *Environmental Pollution*, 292, 118383. doi: 10.1016/j.envpol.2021.118383

Mercer (2019). Quality of living city ranking. Retrived from https://mobilityexchange.mercer.com/insights/quality-of-living rankings#:~:text =of%20living%20ranking-,Quality%20of%20living%20city%20ranking, In%20 light%20of

Met Office (2016). Beaufort wind force scale. Retrieved fromhttps://www.metoffice.gov.uk/guide/weather/marine/beaufort-scale.Mirzaei, P. A., and Haghighat, F. (2010). Approaches to study Urban Heat Island - Abilities and limitations. *Building and Environment, 45*(10), 2192-2201. doi: 10.1016/j.buildenv.2010.04.001

Mirzaei, P. A., and Haghighat, F. (2010). Approaches to study Urban Heat Island – Abilities and limitations. *Building and Environment, 45*(10), 2192-2201. doi: 10.1016/j.buildenv.2010.04.001

Mohan, M., Singh, V. K., Bhati, S., Lodhi, N., Sati, A. P., Sahoo, N. R., ... and Dey, S. (2020). Industrial heat island: a case study of Angul-Talcher region in India. *Theoretical and Applied Climatology*, 141(1), 229-246. doi: 10.1007/s00704-020-03181-9

Morgan, J., Dagnet, Y., and Tirpak, D. (2014). Elements and ideas for the 2015 Paris agreement. Washington, DC: Agreement for Climate Transformation. *Retrieved* from http://www.wri.org/sites/default/files/ACT_Elements_Ideas_FullPaper_FINAL.PDF.

Morris, C. J. G., Simmonds, I., and Plummer, N. (2001). Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *Journal of Applied Meteorology and Climatology, 40*(2), 169-182.

Morris, K. I., Aekbal Salleh, S., Chan, A., Ooi, M. C. G., Abakr, Y. A., Oozeer, M. Y., and Duda, M. (2015). Computational study of urban heat island of Putrajaya, Malaysia. *Sustainable Cities and Society, 19*, 359-372. doi: 10.1016/j.scs.2015.04.010

Morris, K. I., Chan, A., Morris, K. J. K., Ooi, M. C., Oozeer, M. Y., Abakr, Y. A., . . . and Al-Qrimli, H. F. (2017). Impact of urbanization level on the interactions of urban area, the urban climate, and human thermal comfort. *Applied geography, 79*, 50-72. doi: 10.1016/j.apgeog.2016.12.007

Morris, K. I., Chan, A., Salleh, S. A., Ooi, M. C. G., Oozeer, M. Y., and Abakr, Y. A. (2016). Numerical study on the urbanisation of Putrajaya and its interaction with the local climate, over a decade. *Urban Climate, 16*, 1-24. doi: 10.1016/j.uclim.2016.02.001

Mou, B., He, B. J., Zhao, D. X., and Chau, K. W. (2017). Numerical simulation of the effects of building dimensional variation on wind pressure distribution. *Engineering Applications of Computational Fluid Mechanics*, 11(1), 293-309. doi: 10.1080/19942060.2017.1281845

Muhamad, H., Ai, T. Y., Sahid, I., and Mat, N. (2010). Downward movement of chlorpyrifos in the soil of an oil palm plantation in Sepang, Selangor, Malaysia. *Journal of Oil Palm Research*, 22(1), 721-728.

Mukaka, M. M. (2012). A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal, 24*(3), 69-71.

Nanjam, R., and Farnood Ahmadi, F. (2021). A New Spatiotemporal Model for Analyzing the Variations of Urban Heat Islands Using Remotely Sensed Multi Spectral Images: The Case of Mashhad City, Iran. *Journal of the Indian Society of Remote Sensing*, 49(10), 2489-2502. doi: 10.1007/s12524-021-01404-8

Nasir, R. A., Ahmad, S. S., Zain-Ahmed, A., and Ibrahim, N. (2015). Adapting Human Comfort in an Urban Area: The Role of Tree Shades Towards Urban Regeneration. *Procedia - Social and Behavioral Sciences, 170*, 369-380. doi: 10.1016/j.sbspro.2015.01.047

Ng, Y. X. (2015). A study of urban heat island using "Local Climate Zones"–the case of Singapore. *British Journal of Environment and Climate Change, 5*(2), 116-133. doi: 10.9734/BJECC/2015/13051

Oke, T. R. (1982). The energetic basis of the urban heat-island. *Quarterly Journal of the Royal Meteorological Society, 108*(455), 1-24. doi: 10.1002/qj.49710845502

Oke, T. R. (1988). The urban energy balance. *Progress in Physical Geography, 12*(4), 471–508. doi: 10.1177/030913338801200401

Oke, T. R. (2004). Initial guidance to obtain representative meteorological observations at urban sites. *IOM Report 81 Geneva: World Meteorological Organization*

Oke, T. R., Johnson, G. T., Steyn, D. G., and Watson, I. D. (1991). Simulation Of Surface Urban Heat Islands Under Ideal Conditions At Night .2. Diagnosis Of Causation. *Boundary-Layer Meteorology, 56*(4), 339-358. doi: 10.1007/bf00119211

Ooi, M. C. G., Chan, A., Subramaniam, K., Morris, K. I., and Oozeer, M. Y. (2017). Interaction of urban heating and local winds during the calm intermonsoon seasons in the tropics. *Journal of Geophysical Research: Atmospheres, 122*(21), 499-523. doi: 10.1002/2017JD026690

Ooi, M. C. G., Chan, A., Ashfold, M. J., Morris, K. I., Oozeer, M. Y., and Salleh, S. A. (2017). Numerical study on effect of urban heating on local climate during calm inter-monsoon period in Greater Kuala Lumpur, Malaysia. *Urban climate*, 20, 228-250. doi: 10.1016/j.uclim.2017.04.010

Othman, M., Ash'aari, Z. H., Muharam, F. M., Sulaiman, W. N. A., Hamisan, H., Mohamad, N. D., and Othman, N. H. (2016). Assessment of drought impacts on vegetation health: a case study in Kedah. *IOP Conference Series: Earth and Environmental Science, 37*, 012072. doi: 10.1088/1755-1315/37/1/012072

Pakarnseree, R., Chunkao, K., and Bualert, S. (2018). Physical characteristics of Bangkok and its urban heat island phenomenon. *Building and Environment,* 143, 561-569. doi: 10.1016/j.buildenv.2018.07.042

Park, H. S. (1986). Features of the heat island in Seoul and its surrounding cities. *Atmospheric Environment, 20*(10), 1859–1866. doi: 10.1016/0004-6981(86)90326-4

Peel, M. C., Finlayson, B. L., and McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences discussions, 4*(2), 439-473. doi: 10.5194/hess-11-1633-2007

Peng, W., Wang, R., Duan, J., Gao, W., and Fan, Z. (2022). Surface and canopy urban heat islands: Does urban morphology result in the spatiotemporal differences?. *Urban Climate*, 42, 101136. doi: 10.1016/j.uclim.2022.101136

Perera, N. G. R., Emmanuel, M. P. R., and Mahanama, P. K. S. (2012). 576: Mapping "Local Climate Zones" and relative Warming Effects in Colombo, Sri Lanka. *In ICUC8–8th International Conference on Urban Climates. Dublin, Ireland, 6-10 August 2012*.

Perim Temizoz, H., and Unal, Y. S. (2017, April). Assessing the effect of wind speed/direction changes on urban heat island intensity of Istanbul. In EGU General Assembly Conference Abstracts (p. 7438).

Phelan, P. E., Kaloush, K., Miner, M., Golden, J., Phelan, B., Silva, H., and Taylor, R. A. (2015). Urban Heat Island: Mechanisms, Implications, and Possible Remedies. In A. Gadgil and T. P. Tomich (Eds.), *Annual Review of Environment and Resources, Vol 40* (Vol. 40, pp. 285-307). Palo Alto: Annual Reviews.

PLANMalaysia (2006). National urbanization policy 1 (NUP 1). Retrieved from http://www.pmo.gov.my/dokumenattached/Dasar/dpn-engx.pdf.

PLANMalaysia (2016). National urbanization policy 2 (NUP2). Retrieved from https://www.townplan.gov.my/content.php?ID=247.

Półrolniczak, M., Kolendowicz, L., Majkowska, A., and Czernecki, B. (2017). The influence of atmospheric circulation on the intensity of urban heat island and urban cold island in Poznan, Poland. *Theoretical and Applied Climatology, 127*(3-4), 611-625. doi: 10.1007/s00704-015-1654-0

PwC (2017). Greater Kuala Lumpur: bridge between Asia and the world. Retrieved from https://www.pwc.com/my/en/assets/publications/170703-greater-kl-bridge-between-asia-and-the-world.pdf

Rahman, I. A., and Dewsbury, J. (2007). Selection of typical weather data (test reference years) for Subang, Malaysia. *Building and Environment*, 42(10), 3636-3641. doi: 10.1016/j.buildenv.2006.10.004

Rajagopalan, P. (2009). Urban heat island and its impact on building energy consumption. *Advances in Building Energy Research, 3*(1), 261–270. doi: 10.1016/j.energy.2019.02.183

Rajagopalan, P., Lim, K. C., and Jamei, E. (2014). Urban heat island and wind flow characteristics of a tropical city. *Solar Energy, 107*, 159-170. doi: 10.1016/j.solener.2014.05.042

Ramakreshnan, L., Aghamohammadi, N., Fong, C., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Wong, L., Hassan, N. and Sulaiman, N. (2018). A critical review of Urban Heat Island phenomenon in the context of Greater Kuala Lumpur, Malaysia. *Sustainable Cities and Society, 39*(99-113). doi: 10.1016/j.scs.2018.02.005

Ramakreshnan, L., Aghamohammadi, N., Fong, C. S., Ghaffarianhoseini, A., Wong, L. P., and Sulaiman, N. M. (2019). Empirical study on temporal variations of canopy-level Urban Heat Island effect in the tropical city of Greater Kuala Lumpur. *Sustainable Cities and Society*, 44, 748-762. doi: 10.1016/j.scs.2018.10.039

Ren, Z., He, X., Pu, R., and Zheng, H. (2018). The impact of urban forest structure and its spatial location on urban cool island intensity. *Urban Ecosystems*, 21(5), 863-874. doi: 10.1007/s11252-018-0776-4

Rizvi, S. H., Alam, K., and Iqbal, M. J. (2019). Spatio-temporal variations in urban heat island and its interaction with heat wave. *Journal of Atmospheric and Solar-Terrestrial Physics*, 185, 50-57. doi: 10.1016/j.jastp.2019.02.001

Rizwan, A. M., Dennis, L. Y. C., and Liu, C. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences, 20*(1), 120-128. doi: 10.1016/s1001-0742(08)60019-4

Roth, M. (2007). Review of urban climate research in (sub)tropical regions. *International Journal of Climatology, 27*(14), 1859-1873. doi: 10.1002/joc.1591

Roth, M. (2013). Urban Heat Islands. *In Fernando, H. J. (Ed.), Handbook of Environmental Fluid Dynamics Volume 2:Systems, Pollution, Modeling, and Measurements(143-159). New York: CRC Press.*

Roth, M., and Chow, W. T. L. (2012). A historical review and assessment of urban heat island research in Singapore. *Singapore Journal of Tropical Geography, 33*(3), 381-397. doi: 10.1111/sjtg.12003

Rovers, T. (2016). The Impacts of Urban Heat Islands on Northwestern European Cities: Characterising the heat island intensity based on land use data, Lulea University of Technology.

Saimi, F. M., Hamzah, F. M., Toriman, M. E., Jaafar, O., and Tajudin, H. (2020). Trend and Linearity Analysis of Meteorological Parameters in Peninsular Malaysia. *Sustainability*, 12(22), 9533. doi: 10.3390/su12229533

Salata, F., Golasi, I., de Lieto Vollaro, A., and de Lieto Vollaro, R. (2015). How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy and Buildings, 99*, 32-49. doi: 10.1016/j.enbuild.2015.04.010

Salleh, S. A., Abd.Latif, Z., Mohd, W. M. N. W., and Chan, A. (2013). Factors Contributing to the Formation of an Urban Heat Island in Putrajaya, Malaysia. *Procedia - Social and Behavioral Sciences, 105*, 840-850. doi: 10.1016/j.sbspro.2013.11.086

Sanderson, H. (2021). Who Is Responsible for Embodied CO2?. *Climate*, *9*(3), 41. doi: 10.3390/cli9030041

Sang, J., Liu, H., Liu, H., and Zhang, Z. (2000). Observational and numerical studies of wintertime urban boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics, 87*(2-3), 243-258.

Sani, S. (1972). Some aspects of urban microclimate of Kuala Lumpur, West Malaysia. *Akademika, 1*, 85–92.

Sani, S. (1984). Urban development and changing patterns of night-time temperatures in the Kuala Lumpur, Petaling Jaya area, Malaysia. *Jurnal Teknologi, 5*, 27-36.

Sani, S. (1986). Temperatures in kuala lumpur and the merging Klang Valley conurbation, Project report prepared for UNESCO. UKM Press, Malaysia. .

Sani, S. (1987). Urbanization and the atmospheric environment in the low tropics. UKM Press, Malaysia. .

Sani, S. (1991). Urban climatology in Malaysia: An overview. *Energy and Buildings, 15*(1), 105–117. doi: 10.1016/0378-7788(90)90121-X

Santamouris, M. (2015a). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Sci Total Environ, 512-513*, 582-598. doi: 10.1016/j.scitotenv.2015.01.060

Santamouris, M. (2015b). Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. *Energy and Buildings, 91*, 43-56. doi: 10.1016/j.enbuild.2015.01.027

Santamouris, M., Cartalis, C., Synnefa, A., and Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings-A review. *Energy and Buildings, 98*, 119-124. doi: 10.1016/j.enbuild.2014.09.052

Sanusi, A. N. Z., Shao, L., and Zamri, A. A. A. (2014). Seeking underground for potential heat sink in Malaysia for Earth Air Heat Exchanger (EAHE) application. *Australian Journal of Basic Applied Science, 8*(8), 54-57.

Satari, S. Z., Zubairi, Y. Z., Hussin, A. G., and Hassan, S. F. (2015). Some statistical characteristic of malaysian wind direction recorded at maximum wind speed: 1999-2008. *Sains Malaysiana, 44*(10), 1521-1530. doi: 10.17576/jsm-2015-4410-18

Shabanda, I. S., Koki, I. B., Raof, S. F. A., Lee, Y. H., Mainal, A., Abu Bakar, N. K., and Khor, S. M. (2021). Distribution of heavy metals in roadside dust of Petaling Jaya, Malaysia with multivariate and correlation analyses for source identification. *International Journal of Environmental Analytical Chemistry*, 101(2), 184-207. doi: 10.1080/03067319.2019.1661400

Shaharuddin, A., Noorazuan, M. H., Takeuchi, W., and Noraziah, A. (2014). The effects of urban heat islands on human comfort: a case of Klang Valley Malaysia. *Global Journal of Advances in Pure and Applied Science, 2*, 1-8.

Shaharuddin, A., Noorazuan, M. H., and Yaakob, M. J. (2009). Fenomena Pulau Haba Bandar dan isu alam sekitar di Bandaraya Kuala Lumpur. *Geografia: Malaysian Journal of Society and Space, 5*(3), 57-67.

Shaharuddin, A., Noorazuan, M. H., Takeuchi, W., and Noraziah, A. (2014). The effects of urban heat islands on human comfort: a case of Klang Valley Malaysia. . *Global Journal of Advances in Pure and Applied Science, 2*, 1-8.

Siu, L. W., and Hart, M. A. (2013a). Quantifying urban heat island intensity in Hong Kong SAR, China. *Environmental Monitoring and Assessment, 185*(5), 4383-4398. doi: 10.1007/s10661-012-2876-6

Solanki, R., Guo, J., Lv, Y., Zhang, J., Wu, J., Tong, B., and Li, J. (2022). Elucidating the atmospheric boundary layer turbulence by combining UHF radar wind profiler and radiosonde measurements over urban area of Beijing. *Urban Climate*, 43, 101151. doi: 10.1016/j.uclim.2022.101151

Steensen, B. M., Marelle, L., Hodnebrog, Ø., and Myhre, G. (2022). Future urban heat island influence on precipitation. Climate Dynamics, 58(11), 3393-3403. doi: 10.1007/s00382-021-06105-z

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology, 31*(2), 200-217. doi: 10.1002/joc.2141

Stewart, I. D., and Oke, T. R. (2009). Classifying urban climate field sites by "Local Climate Zones", The case of Nagano, Japan. *In: Seventh International Conference on Urban Climate, Yokohama, Japan, 20/6/2009-3/7/2009.*

Stewart, I. D., and Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society, 93*(12), 1879-1900. doi: 10.1175/BAMS-D-11-00019.1

Strategic Planning of Petaling Jaya City Council 2021-2025 (2021). Retrieved from https://www.mbpj.gov.my/sites/default/files/web_buku_pelan_strategik_v01_30092021_.pdf

Sultana, S., and Satyanarayana, A. N. V. (2020). Assessment of urbanisation and urban heat island intensities using landsat imageries during 2000–2018 over a sub-tropical Indian City. *Sustainable Cities and Society*, 52, 101846. doi: 10.1016/j.scs.2019.101846

Tan, K. C., Lim, H. S., MatJafri, M. Z., and Abdullah, K. (2009). Landsat data to evaluate urban expansion and determine land use/land cover changes in Penang Island, Malaysia. *Environmental Earth Sciences, 60*(7), 1509-1521. doi: 10.1007/s12665-009-0286-z

Tan, T. H. (2012). Meeting first-time buyers' housing needs and preferences in greater Kuala Lumpur. *Cities*, 29(6), 389-396. doi: 10.1016/j.cities.2011.11.016

Teck-Hong, T. (2012). Housing satisfaction in medium-and high-cost housing: The case of Greater Kuala Lumpur, Malaysia. *Habitat International*, 36(1), 108-116. doi: 10.1016/j.habitatint.2011.06.003

Thani, S. K. S. O., Mohamad, N. H. N., and Abdullah, S. M. S. (2013). The Influence of Urban Landscape Morphology on the Temperature Distribution of Hot-Humid Urban Centre. *Procedia - Social and Behavioral Sciences, 85*, 356-367. doi: 10.1016/j.sbspro.2013.08.365

The Star (2016, June, 4). Hailstorm and flash flood mayhem in KL. Retrieved from http://www.thestar.com.my/news/nation/2016/06/04/hailstorm-and-flash-flood-mayhem-in-kl-weather-wreaks-havoc-with-traffic-and-rail-service/.

The World Bank. (2015) Malaysia Economic Monitor: Transforming Urban Transport (Bangkok, Thailand: The World Bank). Retrieved from https://www.worldbank.org/en/country/malaysia/publication/malaysia-economic-monitor-june-2015

Thomas, G., Sherin, A. P., Ansar, S., and Zachariah, E. J. (2014). Analysis of Urban Heat Island in Kochi, India, Using a Modified Local Climate Zone Classification. *Procedia Environmental Sciences, 21*, 3-13. doi: 10.1016/j.proenv.2014.09.002

Tso, C. P. (1996). A survey of urban heat island studies in two tropical cities. *Atmospheric Environment, 30*(3), 507-519. doi: 10.1016/1352-2310(95)00083-6

Tso, C. P., and Law, K. Y. (1990). Evaluation of the thermal environment in the building areas of Kuala Lumpur city by a new twin energy balance method. *Energy and Buildings, 15*(1-2), 271-277.

Ulpiani, G. (2021). On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework. *Science of the total environment*, 751, 141727.

United Nations (UN) (2016). UN Daily News: 2016 on pace to be hottest year ever as climate change trends reach 'new climax'. Retrieved from http://www.un.org/News/dh/pdf/english/2016/21072016.pdf.

United Nations (UN) (2015). World Population Prospects: The 2015 Revision, Key findings and advance tables. Department of Economic and Social Affairs, Population Division (ESA/P/WP.241.) Retrieved from https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf.

Urbanice Malaysia and MBSJ Voluntary Local Review (2021) – The implementation of 2030 Agenda for Sustainable Development in Subang Jaya City. Retrieved from https://unhabitat.org/sites/default/files/2021/07/vlr_sdgs_subang_jaya.pdf van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., van Driel, B. L., and Holtslag, A. A. M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment, 83*, 91-103. doi: 10.1016/j.buildenv.2014.08.029

Velazquez-Lozada, A., Gonzalez, J. E., and Winter, A. (2006). Urban heat island effect analysis for San Juan, Puerto Rico. *Atmospheric Environment, 40*(9), 1731-1741. doi: 10.1016/j.atmosenv.2005.09.074

Venter, Z. S., Chakraborty, T., and Lee, X. (2021). Crowdsourced air temperatures contrast satellite measures of the urban heat island and its mechanisms. *Science Advances*, 7(22), eabb9569. doi: 10.1126/sciadv.abb9569

Voogt, J. A., and Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment, 86*(3), 370-384. doi: 10.1016/s0034-4257(03)00079-8

Wang, J., Huang, B., Fu, D. J., Atkinson, P. M., and Zhang, X. Z. (2016). Response of urban heat island to future urban expansion over the Beijing-Tianjin-Hebei metropolitan area. *Applied Geography, 70*, 26-36. doi: 10.1016/j.apgeog.2016.02.010

Wang, Y., Berardi, U., and Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and Buildings*, 114, 2-19. doi: 10.1016/j.enbuild.2015.06.046

Wang, X., Zhang, C., Dong, N., and Yao, W. (2016). Urban heat island effect under different meteorological conditions in Jining of Shandong province. *Nanjing Xinxi Gongcheng Daxue Xuebao*, 8(2), 160. doi: 10.13878/j.cnki.jnuist.2016.02.008

Wang, K., Jiang, S., Wang, J., Zhou, C., Wang, X., and Lee, X. (2017). Comparing the diurnal and seasonal variabilities of atmospheric and surface urban heat islands based on the Beijing urban meteorological network. *Journal of Geophysical Research: Atmospheres*, 122(4), 2131-2154. doi: 10.1002/2016JD025304

Wang, W., and Shu, J. (2020). Urban renewal can mitigate urban heat islands. *Geophysical Research Letters*, 47(6), e2019GL085948. doi: 10.1029/2019GL085948

Wang, Z., Liu, M., Liu, X., Meng, Y., Zhu, L., & Rong, Y. (2020). Spatio-temporal evolution of surface urban heat islands in the Chang-Zhu-Tan urban agglomeration. *Physics and Chemistry of the Earth, Parts A/B/C*, 117, 102865. doi: 10.1016/j.pce.2020.102865

Wang, Z. H. (2022). Reconceptualizing urban heat island: Beyond the urban-rural dichotomy. *Sustainable Cities and Society*, 77, 103581. doi: 10.1016/j.scs.2021.103581

Wong, N. H. (2016). Urban heat island research: Challenges and potential. *Frontiers of Architectural Research, 5*(2), 276-278. doi: 10.1016/j.foar.2016.04.001

Wong, P. P. Y., Lai, P. C., Low, C. T., Chen, S., and Hart, M. (2016). The impact of environmental and human factors on urban heat and microclimate variability. *Building and Environment, 95*, 199-208. doi: 10.1016/j.buildenv.2015.09.024

Yang, B., Zhang, Y., and Qian, Y. (2012). Simulation of urban climate with high-resolution WRF model: A case study in Nanjing, China. *Asia-Pacific Journal of Atmospheric Sciences, 48*(3), 227-241. doi: 10.1007/s13143-012-0023-5

Yang, X., Zhao, L., Bruse, M., and Meng, Q. (2012). An integrated simulation method for building energy performance assessment in urban environments. *Energy and buildings, 54*, 243-251. doi: 10.1016/j.enbuild.2012.07.042

Yang, P., Ren, G., and Liu, W. (2013). Spatial and temporal characteristics of Beijing urban heat island intensity. *Journal of applied meteorology and climatology*, 52(8), 1803-1816. doi: 10.1175/JAMC-D-12-0125.1

Yang, P., Ren, G., and Hou, W. (2017). Temporal–spatial patterns of relative humidity and the urban dryness island effect in Beijing City. *Journal of Applied Meteorology and Climatology*, 56(8), 2221-2237. doi: 10.1175/JAMC-D-16-0338.1

Yang, X., Chen, Y., Peng, L. L., and Wang, Q. (2020). Quantitative methods for identifying meteorological conditions conducive to the development of urban heat islands. *Building and Environment*, 178, 106953. doi: 10.1016/j.buildenv.2020.106953

Yap, J. B. H., Chua, C. Y., and Skitmore, M. (2021). Towards Sustainable Mobility with Transit-Oriented Development (TOD): Understanding Greater Kuala Lumpur. *Planning Practice & Research*, 36(3), 314-336. doi: 10.1080/02697459.2021.1883249

Yew, L. K. (2014). The bigger picture – Looking at Water Issues in their Context, An end to the Selangor Water Saga? *Malaysian Water Association (MWA), Malaysia, Percetakan Osacar Sdn Bhd.*

Yuan, C., Adelia, A. S., Mei, S., He, W., Li, X. X., and Norford, L. (2020). Mitigating intensity of urban heat island by better understanding on urban morphology and anthropogenic heat dispersion. *Building and Environment*, 176, 106876. doi: 10.1016/j.buildenv.2020.106876

Yusuf, Y. A., Pradhan, B., and Idrees, M. O. (2014). Spatio-temporal Assessment of Urban Heat Island Effects in Kuala Lumpur Metropolitan City Using Landsat Images. *Journal of the Indian Society of Remote Sensing, 42*(4), 829-837. doi: 10.1007/s12524-013-0342-8

Zahn, E., Welty, C., Smith, J. A., Kemp, S. J., Baeck, M. L., and Bou - Zeid, E. (2021). The hydrological urban heat island: Determinants of acute and chronic heat stress in urban streams. *JAWRA Journal of the American Water Resources Association*, 57(6), 941-955. doi: 10.1111/1752-1688.12963

Zhang, H., Qi, Z. F., Ye, X. Y., Cai, Y. B., Ma, W. C., and Chen, M. N. (2013). Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Applied Geography, 44*, 121-133. doi: 10.1016/j.apgeog.2013.07.021

Zhao, L., Lee, X., Smith, R. B., and Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature, 511*(7508), 216-219. doi: 10.1038/nature13462

Zhou, L., Dickinson, R. E., Tian, Y., Fang, J., Li, Q., Kaufmann, R. K., . . . and Myneni, R. B. (2004). Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences of the United States of America, 101*(26), 9540-9544.

Zhou, X., and Chen, H. (2018). Impact of urbanization-related land use land cover changes and urban morphology changes on the urban heat island phenomenon. *Science of the Total Environment*, 635, 1467-1476. doi: 10.1016/j.scitotenv.2018.04.091

Zong-Ci, Z., Yong, L., and Jian-Bin, H. (2013). Are There Impacts of Urban Heat Island on Future Climate Change? *Advances in Climate Change Research, 4*(2), 133-136. doi: 10.3724/sp.j.1248.2013.133

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z., and Wei, L. (2020). 2020 may be third hottest year on record, world could hit climate change milestone by 2024. United Nations Sustainable Development Goal. Retrived from http://resp.llas.ac.cn/C666/handle/2XK7JSWQ/306266